WL-TR-96-2078

ANIMATED COMPUTER GRAPHICS
OF ROLLING BEARING DYNAMICS

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JUNE 1996

FINAL REPORT FOR 09/01/92-03/01/96

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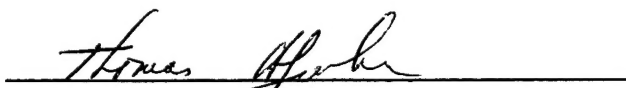WRIGHT PATTERSON AFB OH 45433-7251

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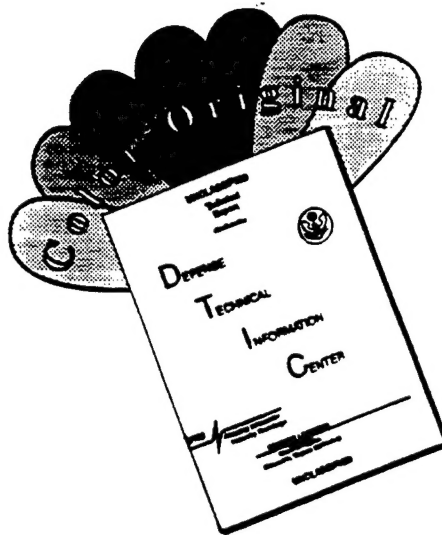
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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED	
	JUN 1996	FINAL	09/01/92--03/01/96

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
ANIMATED COMPUTER GRAPHICS OF ROLLING BEARING DYNAMICS	C F33615-92-C-2294
6. AUTHOR(S) DR. PRADEEP K. GUPTA	PE 65502
	PR 3005
	TA 02
	WU 14

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
PRADEEP K. GUPTA, INC. 117 SOUTHBURY ROAD CLIFTON PARK NY 12065-7714	G-117-TR

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AEROPROPULSION AND POWER DIRECTORATE WRIGHT LABORATORY AIR FORCE MATERIEL COMMAND WRIGHT PATTERSON AFB OH 45433-7251 POC: Garry Givan, WL/POSL, (513)255-1286	WL-TR-96-2078

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.	

13. ABSTRACT (Maximum 200 words)

An animated graphics model has been developed to display the motion and interactions in rolling bearings. Graphics primitives in the standard PHIGS (Programmers Hierarchical Interactive Graphics System) libraries are used to develop graphic structures of the various bearing elements and graphic objects. Components of bearing element motion, as obtained by solution to the classical differential equations of motion for all the bearing elements, are used to edit the local transformation elements in these structures and then refresh the display as a function of time. Thus an animated motion of bearing elements is produced. Graphic capabilities, such as double buffering and z-buffers are used to present a smooth animated video. The net outcome of this project is a computer code AGORE (Animated Graphics Of Rolling Elements) which interfaces with existing bearing dynamics code, ADORE, to display the bearing motions in an animated fashion.

14. SUBJECT TERMS			15. NUMBER OF PAGES
Rolling Bearings	Graphic Animation	Bearing Dynamics	77
Cage Motion	Graphic Visualization		16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

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Foreword

1. Introduction

The main shaft bearings are often identified as critical components of a high performance gas turbine engine. As the operating environments become increasingly adverse, the mechanical, chemical and thermal interactions between the fundamental elements of the bearing become quite complex, and overall behavior of the bearings as a function of the operating environment determines the performance and operating life of the entire turbine engine system. Among the various types of bearings, rolling bearings, due to their high load support, stiffness and speed capabilities, are the most common type of bearings used in turbine engines. In addition, rolling bearings are employed in a wide range of other applications covering a rather large spectrum of operating loads and speeds. The applications include both DOD and commercial systems. Precision gyroscopes and momentum wheels used in communication satellites, helicopter transmissions, auxiliary power units, a wide range of automotive applications, cryogenic turbopumps and related space systems, and more recently the rolling bearings used in computer disk drives, are some examples. Due to such a wide application domain, modeling the performance of rolling bearings has been of significantly increasing interest over the past many years. Sophisticated mathematical and numerical procedures have been developed to model the subtle kinematic and dynamic phenomena in rolling bearings. The procedures have been implemented in advanced computer codes which integrate the classical differential equations of motion of the bearing elements to model the overall dynamic performance of the bearings under complex operating environment. However, as the complexity of the model increases, the results or performance predictions of a model also become quite complex and the need for computer tools to interpret the model predictions in very practical terms becomes vital to effective design and performance simulation. The commonly used computer print outputs or conventional two or three dimensional graphical representation of certain performance parameters become inadequate to fully comprehend the subtle interactions which are fundamental to the overall performance of the bearings. Such problems associated with the practical interpretation of the model predictions are more obvious when the advanced computer codes are used by bearing engineers for practical designs. With the advent of modern computer graphics technology, animated display of the dynamic motions, as predicted by the computer codes, provides the necessary bridge to effectively transfer the advanced technology to real practical system. Such a pictorial representation provides a very lively perspective of the overall bearing behavior and it requires minimum imagination from a designer to implement the most advanced technology to practical systems. The development of such animated graphics tools for rolling bearings has, therefore, been the primary objective of this project. In the related Phase I effort [1] the motions of balls and cage in an angular contact ball bearing were simulated in two dimensions to demonstrate the technical feasibility of the overall modeling approach, while a more comprehensive effort required to develop a generalized graphics animation model is the subject of the current Phase II effort.

Over the past decade a significant advancement has been made in modeling the complex dynamic behavior of rolling bearing elements. Computer codes, which integrate the differential equations of motion of the bearing elements and thereby provide a real-time simulation of bearing performance are now fairly widely used in the industry. However, as the motions become complex, it becomes increasingly difficult to relate the results to critical design parameters and the

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need for animated pictorial display becomes obvious. For example, a combined whirl and rotational motion of the cage is hard to visualize from graphs which just show the variations in velocity and position as a function of time. Animated display on the other hand may show the moving cage in a three dimensional space. Thus no imagination on part of the bearing designer is required in order to fully comprehend the actual motion. Generally the graphics model takes the fundamental components of bearing element motion as inputs to compute the various transformations which are applied on the graphics objects to produce the animated motion. While the computer codes, such as ADORE[2], provide the basic components of motion of the bearing elements. The rapidly advancing computer hardware, and the emerging graphics software standards provide the tools required for the development of animated graphics software.

The recent advances in Unix based computer graphics workstations have resulted in both the computational speed and graphics capabilities required to draw the images at a rate fast enough for a lively visualization of the simulated motion. The RISC (Reduced Instruction Set Computer) based processors offer compute speed which is close to that available on a wide range of mainframe computers. In addition, graphics hardware options such as double buffering and Z-buffers provide high-speed image processing required for animated graphics. In the software area, the graphics primitive tools, such as GKS (Graphics Kernel System), and PHIGS (Programmers Hierarchical Interactive Graphics System) are fairly standard on a wide range of computer systems. Thus the software portability from one system to the other is greatly eased. In the present effort, the available bearing dynamics computer code ADORE [2] is used to generate the time-varying motions of the rolling elements and cage in both ball and roller bearings; using the graphics primitives available under the PHIGS standard, computer subprograms are written, to generate images of the bearing elements and prepare graphics "structures"; appropriate transformation algorithms which take the motion generated by ADORE and edit the various graphics structures are developed and coded into subprograms; finally, the transformation codes and the element image codes are combined to generate the animated graphics model for the bearing. An IBM-RISC/6000 computer work station is used in the present project. However, all the computer codes developed are actually machine independent. For simplicity, and for the purpose of proving the technical feasibility of the overall approach, all transformations and imaging were restricted to two dimensions in a plane normal to the bearing axis, during the first phase [1] of this development. In addition, the graphics model was restricted to ball bearings during the initial feasibility phase. Having proven the technical feasibility, a more extensive graphics model development to display all significant interactions between bearing elements, in ball, cylindrical and tapered roller bearings, and present a clear visualization of cage motion in a three dimensional space with arbitrary view angles has been the objective of the present effort. While maintaining some similarity with the bearing dynamics code, ADORE, the generalized graphics model has been named AGORE (Animated Graphics Of Rolling Elements).

2.   Technical Approach

Animated graphics simply consists of display of a graphic object with varying position and orientation. An object is first drawn with the initial orientation, the screen is erased and then the object is redrawn with an altered orientation. If this process is repeated fast enough, approximately thirty times a second, the display will show a moving picture to the human eye. Thus the base images and the mechanics of changing the orientation of the image are the two components of the animated graphics model. In a greatly simplified form the overall approach may be schematically presented in figure 1. First a data base consisting of the various graphics components, or images, is constructed. In order to generate a particular image, desired by the user, the relevant components are then selected and drawn at prescribed orientation; very often more than one image may have to be processed to generate the required composite picture. Finally, this assembled picture of the base components is projected to the active display. Control is then passed to the component selection module for the next operation and the process continues in a loop.

Implementation of the above general approach requires both software and hardware standards, when portability of the model between different computer systems is desired. For the present investigation the software development is based on the ISO PHIGS (Programmers Hierarchical Interactive Graphics System) standard and the widely used IBM RS/6000 workstation, operating under a Unix (IBM AIX) operating system, is used as the base hardware. All codes are written in standard ANSI C language for easy portability. PHIGS implementation, under Unix, is available on any workstation. Thus portability of the computer graphics model resulting from the present investigation is quite straightforward.

In terms of the PHIGS terminology, the basic components of an animated graphics model consist of (1) the graphics structures, (2) transformations, and (3) user input control. The approach in each of these basic areas is presented below.

2.1 PHIGS Graphics Structure

In the PHIGS terminology a "structure" is a collection of graphic primitives with prescribed attributes. Both the primitives and attributes are editable in a graphic structure. The fundamental primitives, available in the PHIGS library, are used to create a graphics structure of the various elements in the bearings., e.g., ball, rollers, cage, races. Also, other structures to display data or key interactions in the bearing are similarly created. In order to permit reorientation of a given component, the "set local transformation" primitive is inserted along with a label primitive, which easily locates the particular transformation element. Creation of all the required structures constitutes the first box (Basic Graphic Components) in figure 1.

Once the graphics structures are created, they may be selectively assembled to create different views as desired by the user. Basically, depending on user options, a few of the structures are selected, appropriate editing of the transformation elements is performed to provide the correct orientation of the components, and then the edited graphics structure is posted to the workstation to provide a display.
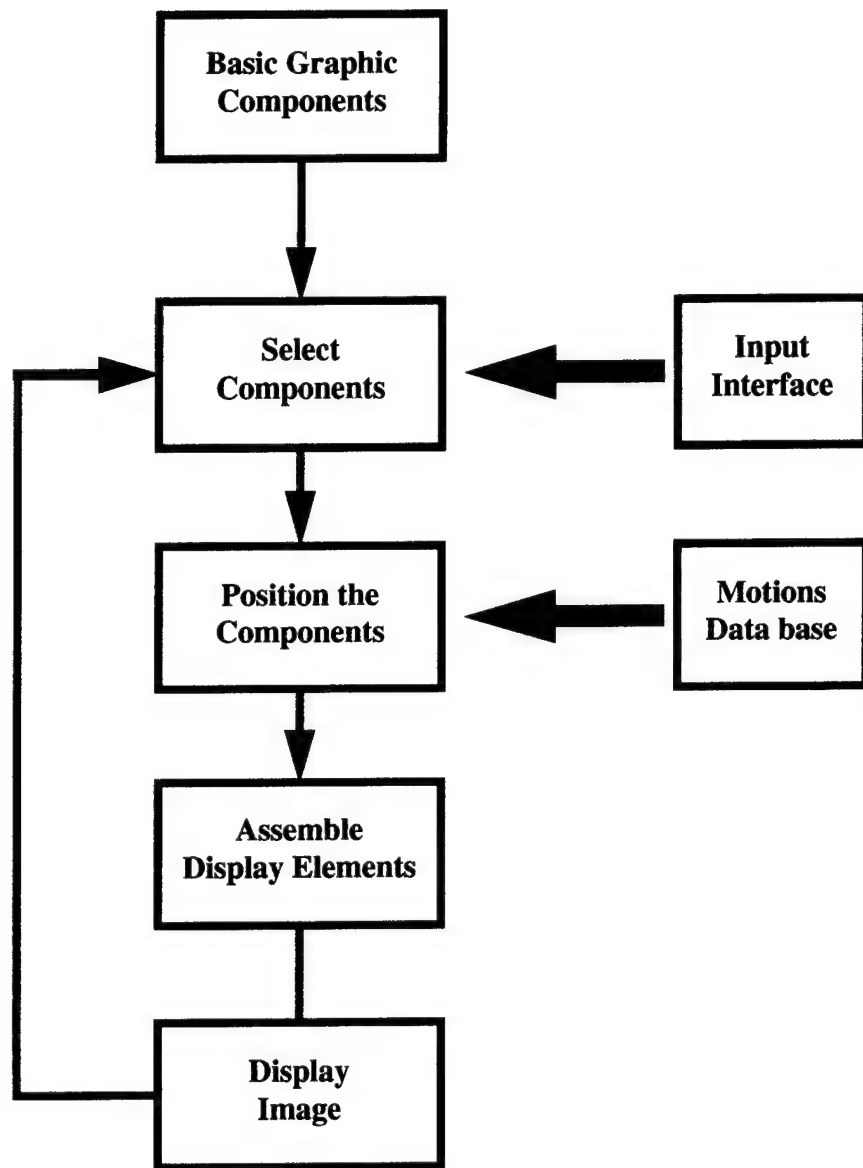
Figure 1
Overall approach to animated graphics model development.

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2.2 Transformations

Transformations in the PHIGS standard are simply matrices generated from the position and angular orientation of a given object. In bearing dynamics code, such as ADORE, the element motion may be computed in a six-degrees-of-freedom system, which consists of three position coordinates and three angles which define the angular orientation. Thus these coordinates are available in the motion data base generated by the bearing dynamics code. With these coordinates, the procedures available in the PHIGS library are used to generate appropriate transformation matrices. In fact these procedures are identical to those used in ADORE [2]. This makes the interface between ADORE output and PHIGS procedures quite straight forward. Analytical details of these transformations are omitted here because they are documented in ADORE [2], a number of computer graphics texts [3] and also in most PHIGS documentation.

The approach to application of a transformation consists of opening the structure, locating the desired transformation element, deleting the old transformation, inserting the new transformation in its place, and closing the structure. Once all the relevant structures are edited with appropriate transformations, they may be assembled to create a desired view.

2.3 User Input Control

Since there are a number of different views and imaging options, a graphic user interface, which permits selection of various options is desired. In the present development, this is accomplished by creating menu button structures in a designated area of the monitor screen. Anytime the mouse is clicked over any of the buttons, the model identifies the mouse pointer location and correlates it to the desired option. The color of the mouse buttons and their borders is appropriately changed to indicate the select or deselect status of a given option. This is also accomplished by editing the button structures. The input control panel is always visible, so that the selected options are clearly visible to the user; in addition, selection of other options is always available.

2.4 Model Overview

With the understanding of the above basic parts to the model, figure 2 presents a simplified overview of the model. The bearing dynamics code is first used to compute the motions data base, which is input to the graphics model to produce the animated displays. A more detailed outline of the overall approach is schematically shown in figure 3. The bearing dynamics computer code ADORE is executed to generate the simulated dynamic motion of bearing elements. The output is compiled in the form of a data base which contains the fundamental components of motion of all bearing elements. The PHIGS primitives are used to develop the graphics codes which generate the shape of bearing elements from the prescribed geometry. The output from these codes, e.g., shape of the bearing elements, can be stored in structures in the computer memory. The data base, obtained by executing ADORE, is now used to generate the transformation coordinates as a function of time. These transformations are then applied on the appropriate graphic structures by using the available editing functions. Finally, the modified images are displayed on the computer monitor. The process is repeated for each time step and the image is continuously refreshed. Thus an animated view is seen on the monitor.
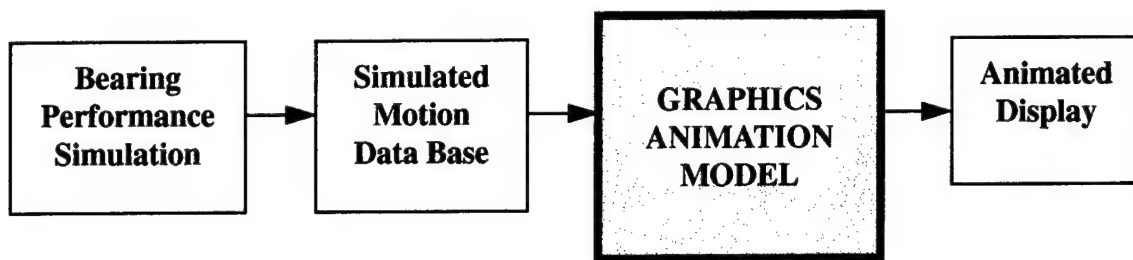
Figure 2
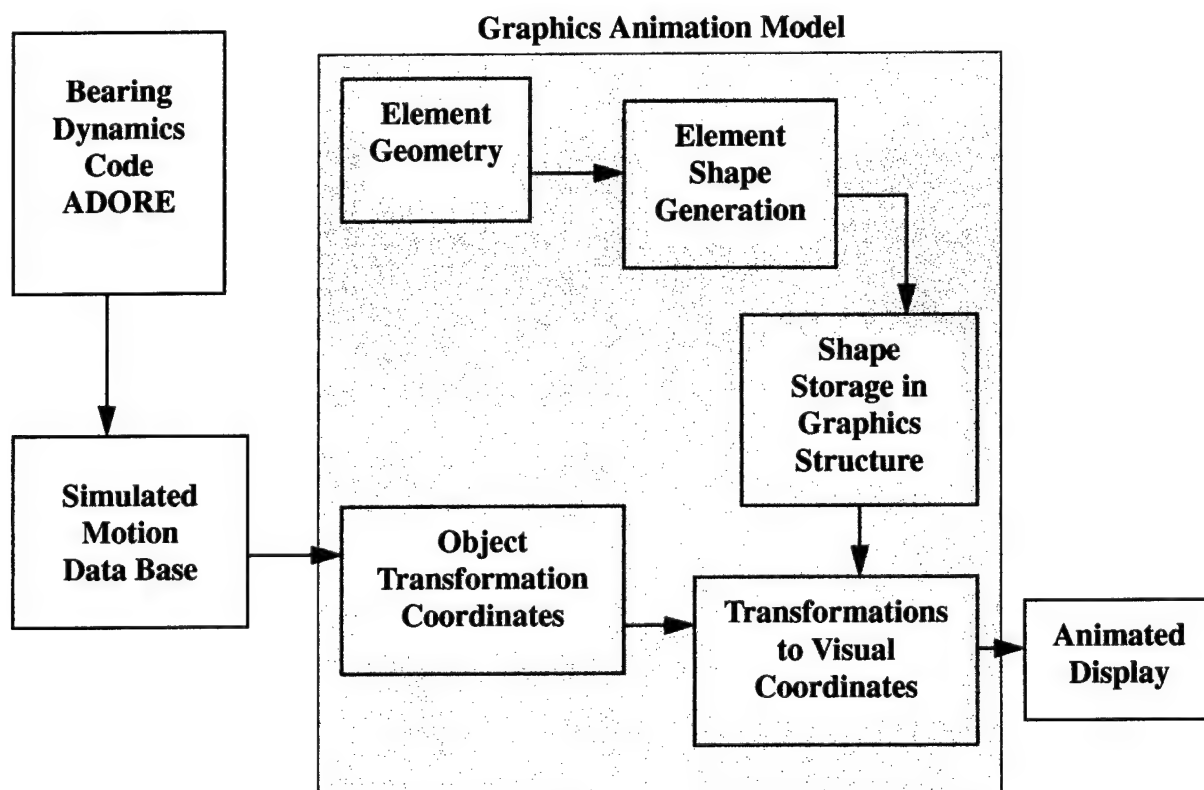**Overview of the approach to graphics animation modeling.**

Graphics Animation Model

Figure 3
Schematic outline of the graphics animation model.

3. Graphics Model Development

The graphics model development process can be best described in terms the following parts:

1. View definitions and the graphics screen
2. Rolling element structures
3. Cage structures
4. Race structures
5. Assembled bearing views

The first part essentially defines the view screen and subdivides it into different regions, which are accessed by the various parts of the model. Parts two to four set up the component images for the rolling element, cage and races respectively. Finally the last part calls on the other more fundamental modules to display the entire bearing.

3.1 View Definitions

The graphics view area is divided into three main parts which constitute the three fundamental view definitions used in the model. Figure 4 shows the typical screen. The main graphics area, where the bearing view is displayed in figure 4, takes up 80% of width and 90% of height of the total display surface. The remainder 20% of the width of the right contains the input options panel and the 10% of display surface height in the bottom part of the screen constitutes the data display area where key performance parameters relevant to the graphics display may be presented.

3.1.1 Main Graphics Area

Generally most monitors have a rectangular display area which results in different scale factors in the horizontal and vertical directions when the scaling is done relative to the maximum available width and height. In other words both the x (horizontal or width) and y (vertical or height) coordinates vary from 0 to 1. If these scales are used to draw the graphic images certain distortion will be eminent. For example all circles will appear as ellipse. In order to eliminate this problem the main graphics area is subdivided into several parts; the top title area, the lower time bar area, the main graphic display area in the middle and an unused area on the right of the main graphics area. Figure 5 shows the different areas of the screen. The main graphic display area is always square with identical scale factors in the x and y directions; actual size of these different zones depend on the available monitor. The following steps are implemented in the graphics model to define the different areas:

1. PHIGS inquiry function is used to determine the available graphics area and appropriate dimensions of the maximum x and y limits are computed so that the screen dimensions per unit real length in both directions are equal. This permits scaled drawing of graphic objects and also the model uses the total available graphics area.

2. With Xmax and Ymax as the maximum x and y limit computed above in step 1, the main graphics area is defined with x and y dimension of 0.80*Xmax and 0.90*Ymax respectively. This

Advanced Dynamics Of Rolling Elements
ADORE-3.5
Cyl Roller Bearing Test Case

Options...

Cage
Poc #
RE #
FlangeInt
OuterRace
InnerRace

Reverse
Step
Continue

EXIT

ORace
CRC Pos
IRaces
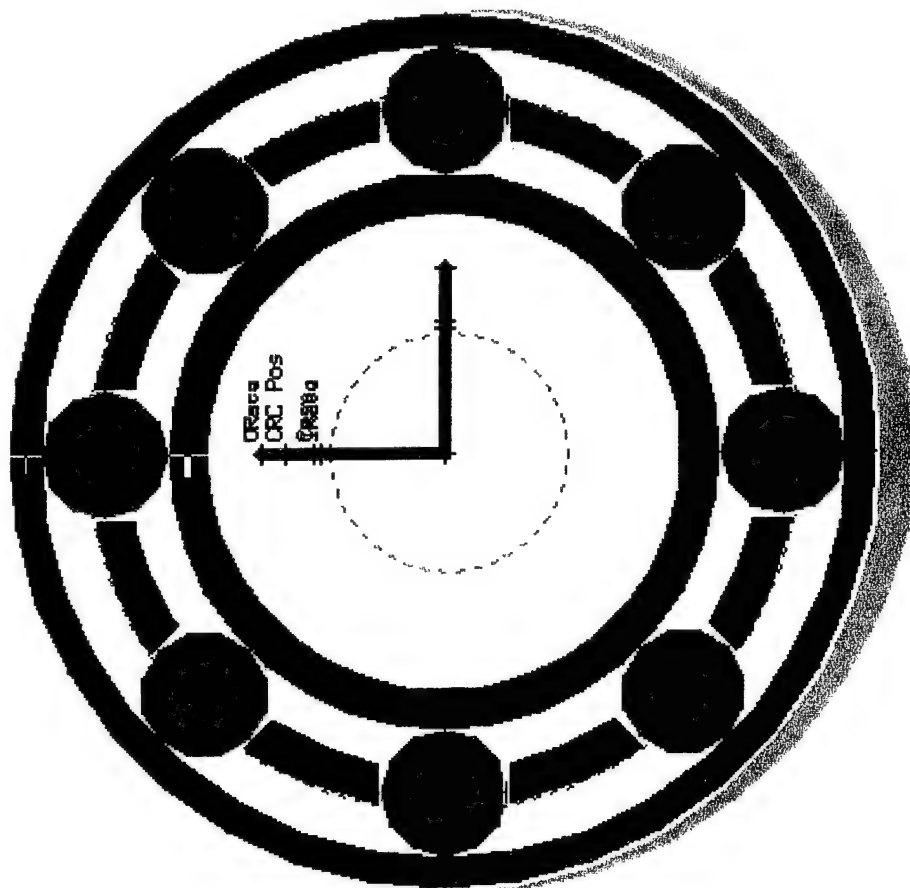
Finish

Start   Bearing Rotation (REVS) =   0.00

Cage/Race Force (N) ×10¹

0   2   4   6   8   10

Land #1
Land #2

Figure 4
Typical display screen.

8
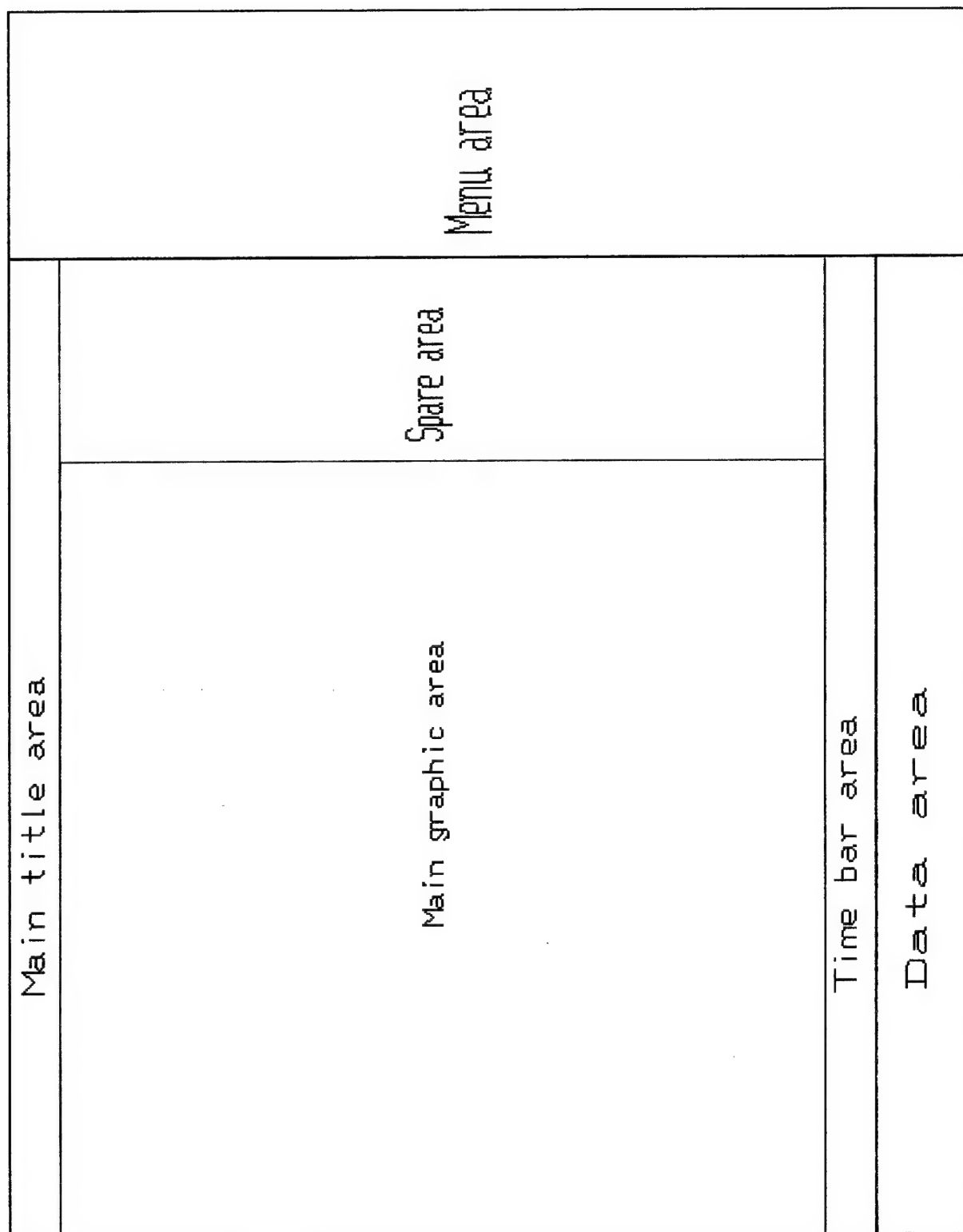
Figure 5
Schematic subdivision of the graphics screen.

main graphics area is subdivided into a square graphics display area with x and y dimensions of 0.88*0.90*Ymax. This leaves some margins on the top for title and at the bottom for the time bar. The remaining panel of the right of the graphics area of size (Xmax - 0.88*0.90*Ymax - 0.80*Xmax) x 0.90*Ymax is presently left blank. the graphics area is now rescaled with screen coordinates varying from -1 to +1 in both x and y directions.

3. The data area has a size of (0.80*Xmax) x (0.10*Ymax). This area is scaled such that the screen dimensions vary form 0 to 1 in both x and y directions.

4. Size of the input panel is (0.20*Xmax) x Ymax. This panel is also scaled to get the screen coordinates to vary from 0 to 1 in both directions.

5. Appropriate view orientation matrices are defined for all the above scale factors and display surface dimensions, and PHIGS procedures are used to assign a view identifier to each of the above views.

6. In addition to above a three dimensional view is also defined over the graphics area computed in step 2. Thus the graphics area could be associated with either 2-D or a 3-D view.

Figure 5 shows the screen sudivision schematically.

3.1.2 Data Area

The data area, located in the bottom of the screen, is used to display two performance parameters relevant to the image in the main graphics area. The parameters are simply plotted as bar charts where the length of bar varies with the varying performance parameter. For the full bearing view, seen in figure 4, the parameters plotted are cage/race forces at the two guide lands on either side of the cage. Data contents for other displays will become clear later as we discuss the pertinent views.

3.1.3 Input Options Panel

The input panel on the right of the display, as seen in figure 4 contains all the input options. The various options are implemented by simple buttons which are invoked by a mouse click on the button area. The options are quite self-explanatory in figure 4.

3.1.4 View Angles for 3-D Views

In addition to the display area or volume, 3-D viewing also requires view angle transformation. This is defined by three angles which can locate the object relative to the eye. These angles are programmed on the valuator dials 1 to 3. Thus when viewing 3-D motions these dials may be turned to change the angular orientation of the viewer relative to the object. The 3-D model only uses parallel projections; therefore, the distance between the object and viewer has no significance. This of course, becomes important in perspective viewing.

3.2 Rolling Element Structures

The rolling element structure is used in several 2-D displays. The structure, therefore, consists of a fill area set defined by a 2-D polygon.

3.2.1 Ball

Two dimensional view of a ball is simply a circle, which can be represented by a polygon. The circularity, of course, depends on the number of sides in the polygon. Figures 6a and 6b show the fill area sets created respectively by 12 and 36 sided polygon. An annotation text element is used to label the rolling element. Also, a "plus" symbol is drawn at the center, primarily to display rotation of the ball. As the ball rotates this symbol will rotate, while the label only translates with the ball center, so that the label is readable when the ball is rotating.

A local transformation element is inserted at top of the structure to simulate both translation and rotation of the ball. As the ball translates and rotates, this matrix is simply recomputed and replaced in the structure.

3.2.2 Rollers

In the 2-D view of the bearing in a plane normal to the shaft axis, the roller also appears as a circle. Thus a structure identical to that discussed above for a ball is used. In the roller/cage and roller/flange interaction views, a cylindrical roller will appear as a rectangle while a tapered roller will be somewhat of a parallelogram. Both these views may be simply displayed by a fill area set created by a polygon with four sides, as shown in figure 7.

The local transformation element at top of this structure contains translation of the roller center relative to the cage pocket center and skew of the roller, which represents rotation about a radial axis through the pocket center. Again the transformation matrix is updated with the pre-scribed coordinates to create the animated views.

3.2.3 Rolling Element/Race Interaction

In addition to the rolling element, this display consists of several other structures, as seen in figure 8. The rolling element/race contact angles are displayed at the center of the diagram by simple load lines, the orientation of which corresponds to the contact angles; the "graduated wheel" shows the magnitude of the angles. The two fill area sets, for both outer and inner race contacts, corresponds to contact pressure and maximum slip, or sliding velocity, in the contact; the height of these rectangular fill areas are edited with the actual values as a function of time to display varying loads and slip velocities. The scales used to determine the fill area size are also included in the legend printed on left of the diagram. In fact, the values printed in the legend are maximum values encountered during the simulation. The moving arrow in the center of the diagram represent orientation of the rolling element angular velocity vector. A projection of this vector on a plane normal to the rolling element axis is shown to the right of the display. The point on this projection will trace a circle if the rolling element is subjected to a coning motion.

A graphic structure is created for each one of the element, discussed above, with appropriate local transformation matrices. These matrices are updated to simulate motion. The entire display structure is just a combination of these substructures.

The data area, in the lower part of the display, contains the rolling element orbital and angular velocities.

Figure 6a
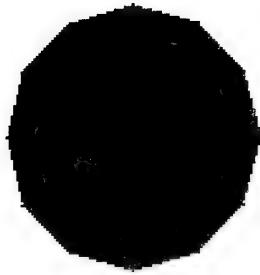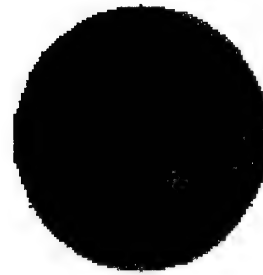**Fill area created by a twelve sided polygon.**

Figure 6b
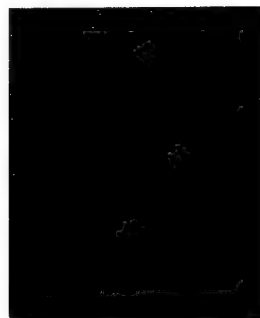**Fill area created by a thirtysix sided polygon.**

Figure 7
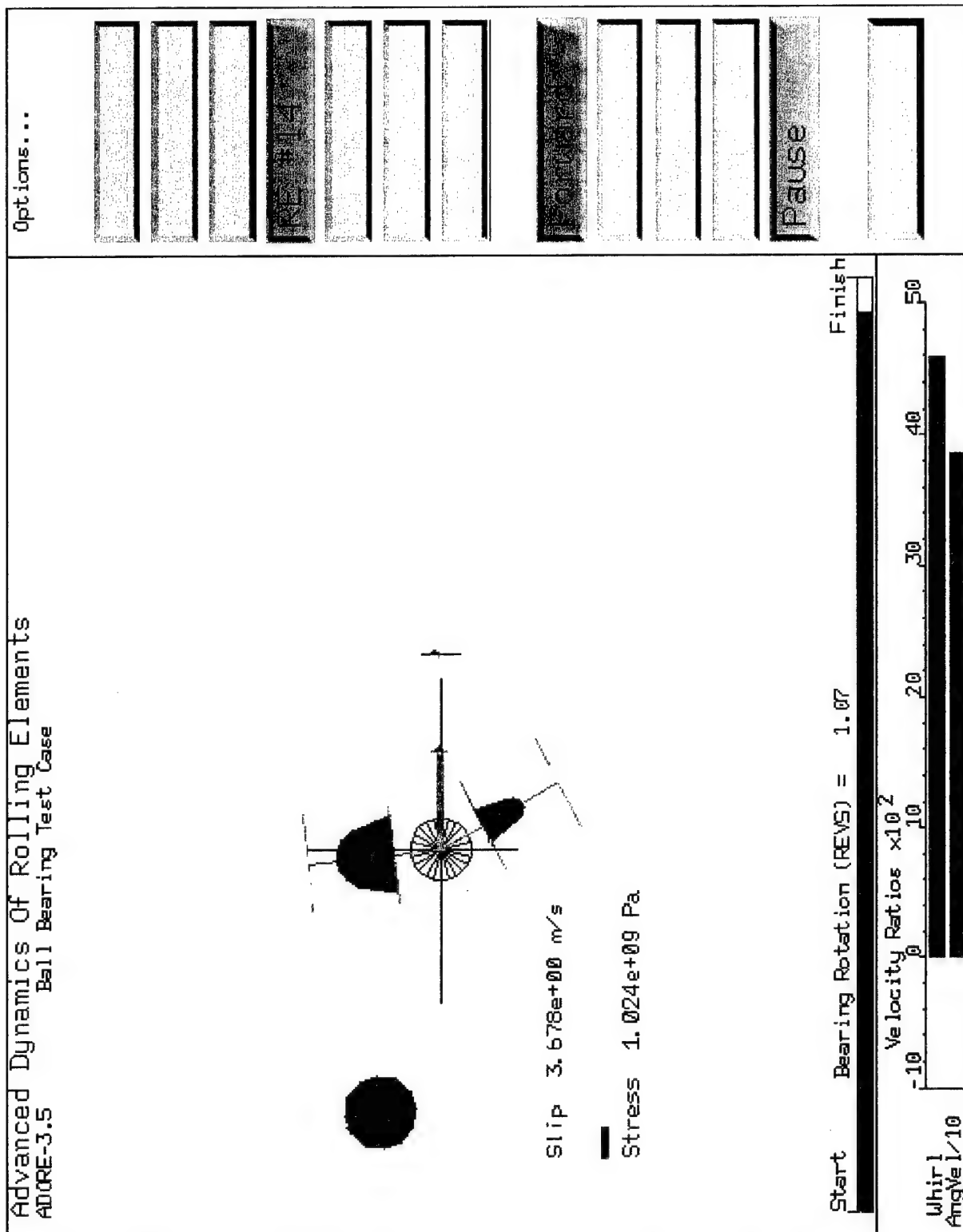**Roller structure created by a rectangular fill area.**

Figure 8

Typical rolling element to race interaction view.

3.2.4 Roller/Flange Interactions

Roller flange contact view is another display consisting of 2-D polygons fill area sets. The roller position and orientation is displayed relative to the guide flange. Thus geometry of the guide flange on the race is fixed, while a local transformation element at top of the roller structure contains both the translational and rotational components of roller motion as applicable to this view. In view of the fact that the magnitude of relative motion is generally very small in comparison to the actual geometry, the rollers essentially appear to be fixed. However, the variation in contact force, shown in the data area indicates varying position of the roller relative to the guide flange on the races. Figures 9a and 9b show a typical view for a cylindrical and tapered roller bearing respectively. The central part of the graphic displays shows the contact load distribution on the race and the roller positions between the guide flanges as seen in the plan view. Any tilt of the roller in view represents roller skew.

3.3 Cage Structures

The cage structure is composed of "sectors" or wedges. Each sector contains a pocket and it extends half way into the wall thickness on either side. Once the graphic elements are assembled for one sector, the process is simply repeated for the number of pockets to obtain the full cage structure. Cage motion is modeled in both two and three dimensions. Thus there are two different structures:

3.3.1 2-D Cage

Figure 10a shows a typical cage pocket structure. It essentially consists of polygon fill area sets. The two areas on either side constitute half of the cage wall, the central area is the cage pocket, and the two rectangular panels in the pocket are used to indicate cage pocket contact. Normally the color of these panels is the same as that of the cage. When a contact takes place the color is changed to red. Thus the pocket is clearly highlighted when a contact exists. This is simply accomplished by inserting a label element before setting the fill area interior color. If a contact in a given pocket exists, then the structure pointer is set to the label and the fill area interior color element is replaced by the desired color.

For a cage with a given number of pockets the graphic elements for a single pocket, or a sector, are executed at different angular positions to generate the entire cage structure. Figure 10b shows the result. At the center of the cage is a coordinate frame, which is fixed in the cage and an arrow, normally red in color. This arrow points in the direction where cage/race geometrical interaction is a minimum, indicating a possible contact. Again this is accomplished by inserting a local transformation element before the graphic primitives creating the arrow. Orientation of this load arrow relative to the cage fixed coordinate frame indicates the point of contact on the cage. Thus if this relative angular position remains fixed the cage will be contacting the guide land at one point only, indicating a possible cage wear problem. A uniform contact around the cage will result in continually varying angular orientation of the load arrow.

At the top of the cage structure is of course the local transformation element which accounts for cage translation and rotation. This matrix is edited with prescribed coordinates to create the animated motion.

Figure 9a

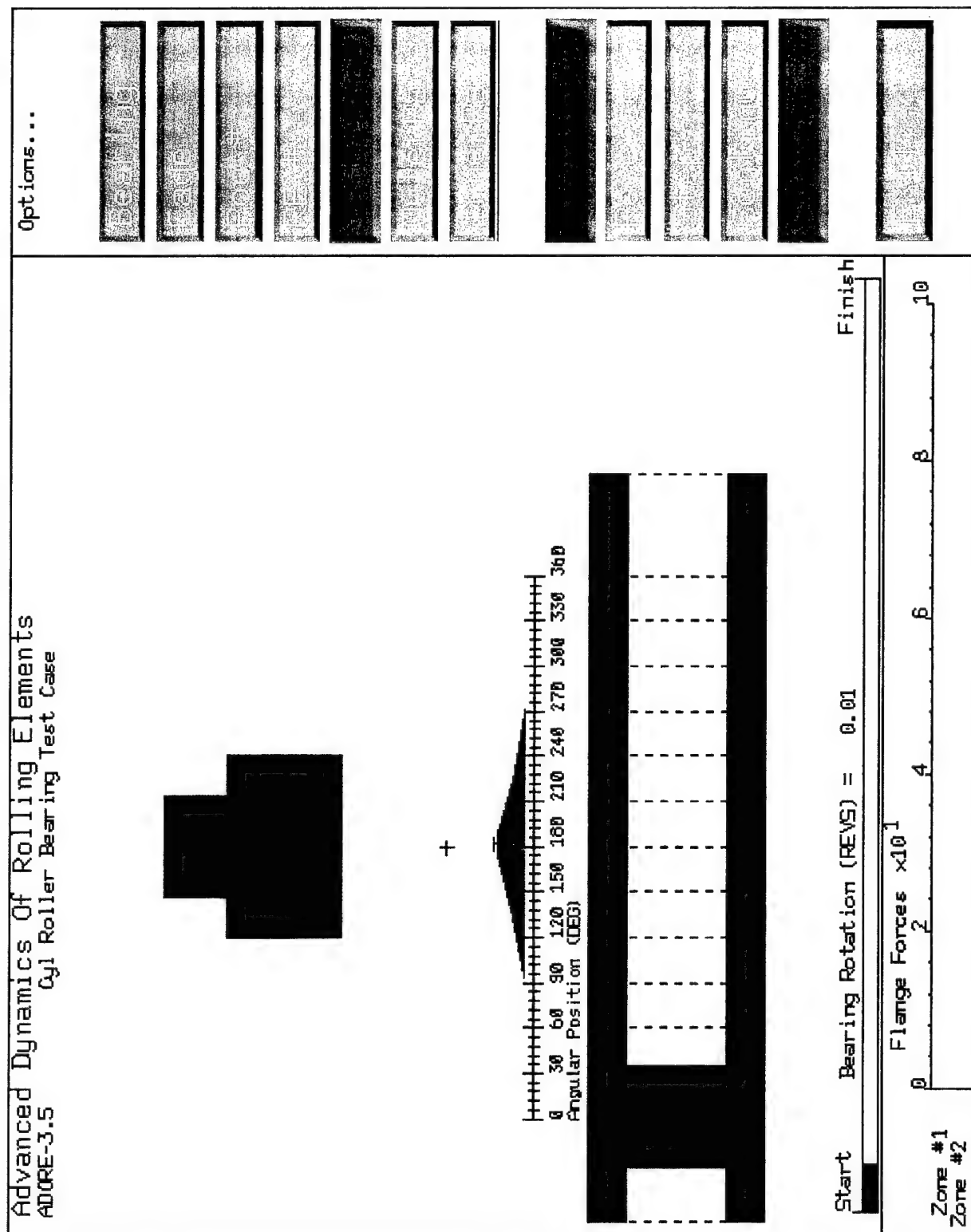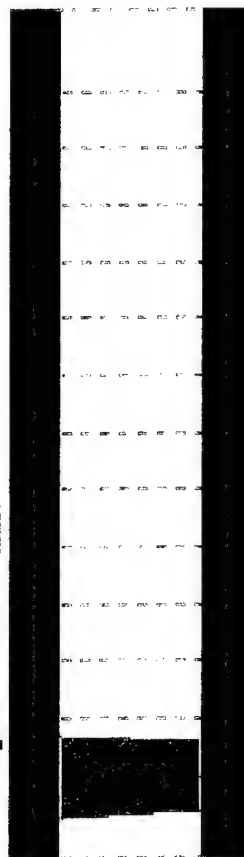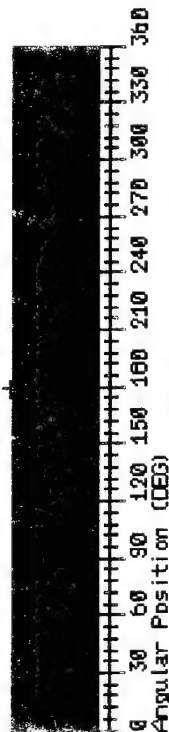**Roller/flange interaction model for cylindrical roller bearings.**

Figure 9b

Roller/flange interaction model for tapered roller bearing.
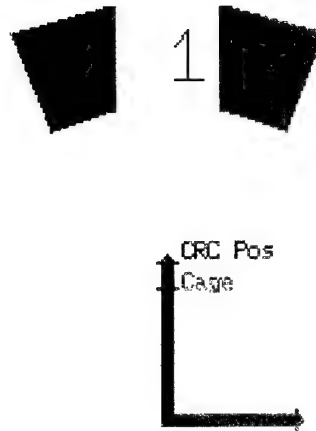
Figure 10a
2-D graphic elements for a cage pocket.

Figure 10b
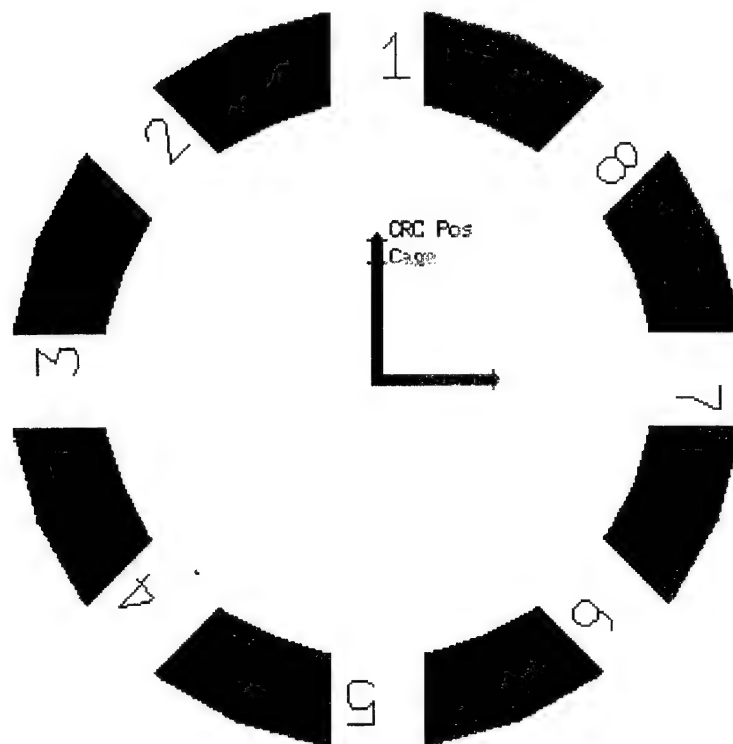**Fill areas in the 2-D cage structure.**

3.3.2 3-D Cage

Graphic model for the 3-D cage is similar to the 2-D formulation discussed above, except that the polygon fill areas are now in a 3-D space. Figure 11a shows the pocket sector consisting of 3-D rectangular fill area sets. No pocket highlighting is considered in 3-D because it the contact location may not always be visible. The primary purpose is to display the motion in 3-D; details of pocket interactions will still be obtained from the 2-D displays.

Again by executing the graphic elements of the sector shown in figure 11a, at different angular positions, the entire cage may be built in 3-D as shown in figure 11b. The local transformations at top of this 3-D structure is of course in 3-D so that the generalized translation and rotation may be modeled. Also, absent from the 3-D structure is the load line, the significance of which is also restricted to the 2-D views.

3.3.3 Cage Motion

Cage motion may be viewed either in a two or three dimensional space. The option is selected by clicking the cage button on the user input panel. Figure 12a shows the motion in two dimensions in a plane normal to the bearing axis. Translation of the mass center is drawn at an enlarged scale so that the whirl motion may be more clearly appreciated. The whirl orbit is drawn in the center of the display. Pocket highlighting is still on. For example, in figure 12a, pockets #8 and #9 are highlighted to indicate that there is a contact in this pocket. Cage whirl and angular velocities are plotted in the data area. Both velocities are shown as a ratio to the shaft rotational speed.

By clicking the cage button on the input panel, the 3-D motion may be turned on, as shown in figure 12b. This view shows the motion in three dimensions. The whirl orbit drawn in the center of the display is now in a three dimensional space. The mass center translation is again drawn at an exaggerated scale to amplify the motion. There is no highlighting of the pockets in the 3-D view. The data area again contains cage whirl and angular velocity ratios.

Interactions in the cage pockets may be seen by clicking the cage pocket button. Typical views are shown in figures 13a and 13b for ball and roller bearings respectively. The cage area in these displays is stationary while the rolling element moves relative to the pocket center. Thus the rolling element to cage collision can be closely traced. Upon contact the resulting contact force is displayed in the data area.

3.4 Race Structures

Similar to other elements, the race structure is also basically a polygon fill area set. The cylindrical geometry is represented by a polygon with 36 sides. A small rectangle is drawn on the face so that rotation of this element may be seen. Figure 14 shows the structure for the inner race. The dotted circle around the race indicates location of the cage/race guide surface. Outer diameter of the cylindrical element is the race diameter in the groove which means that part of the race is actually removed. This is done so that the rolling elements may be seen fully in the assembled bearing view. A race fixed coordinate frame is drawn at center of the race; as the race rotates the coordinates frame rotates with it.
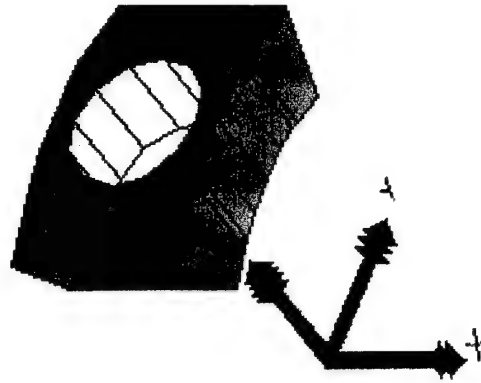
Figure 11a
3-D graphic elements for a cage pocket.
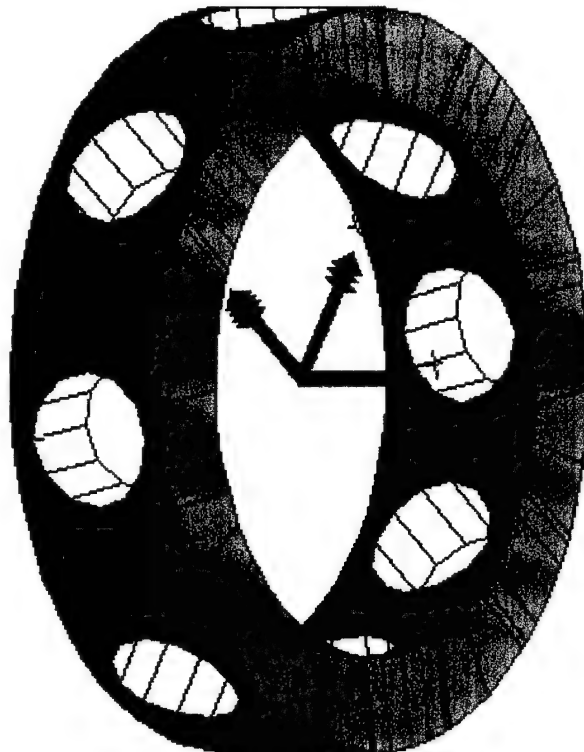
Figure 11b
Cage structure based on 3-D polygon fill areas.
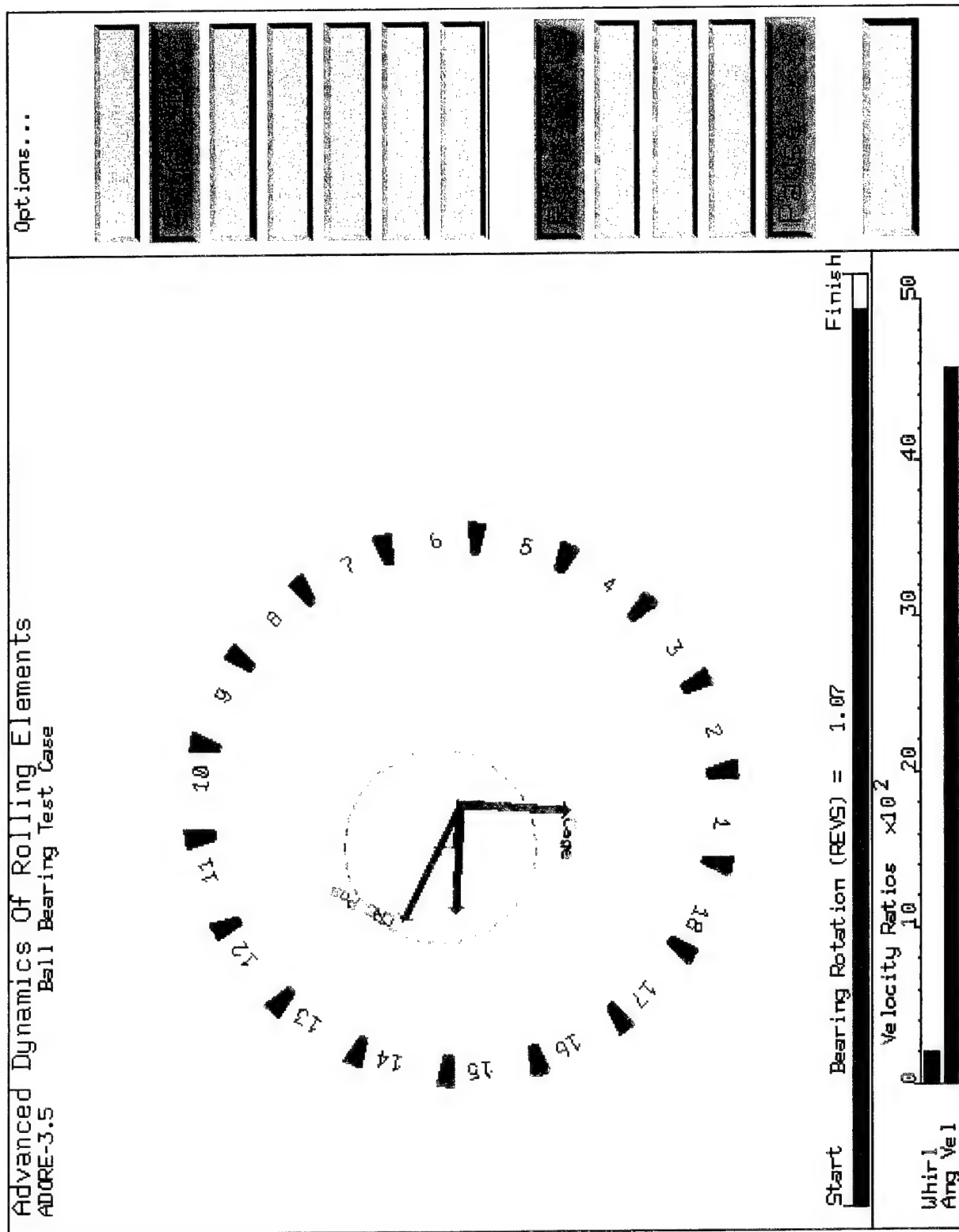
Figure 12a

Typical cage motion in a two-dimensional space.

Figure 12b

Cage motion display in three-dimensional space.

21
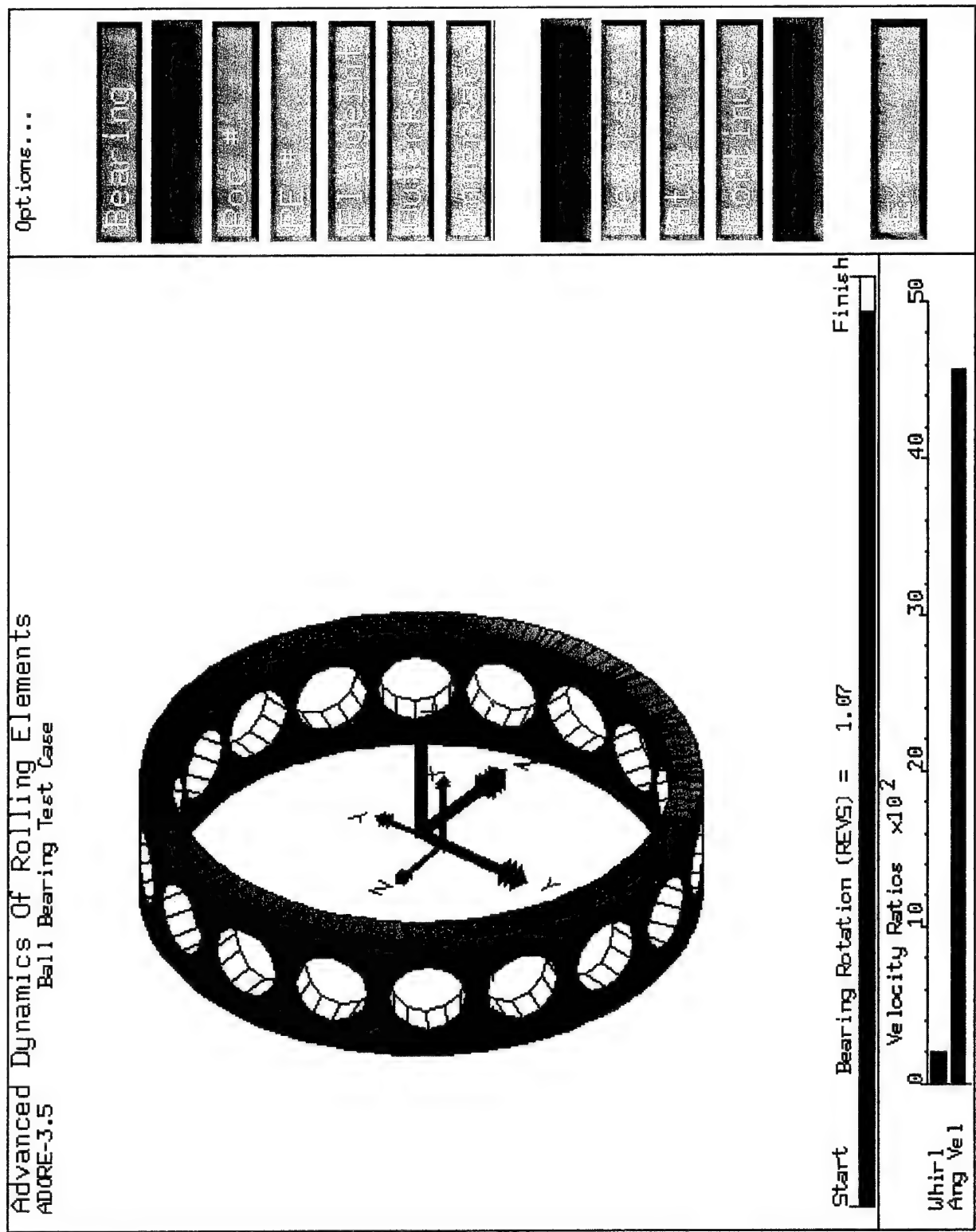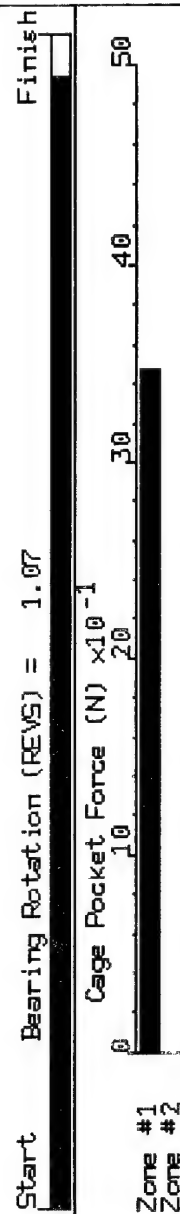
Figure 13a
Typical view of ball pocket structure.
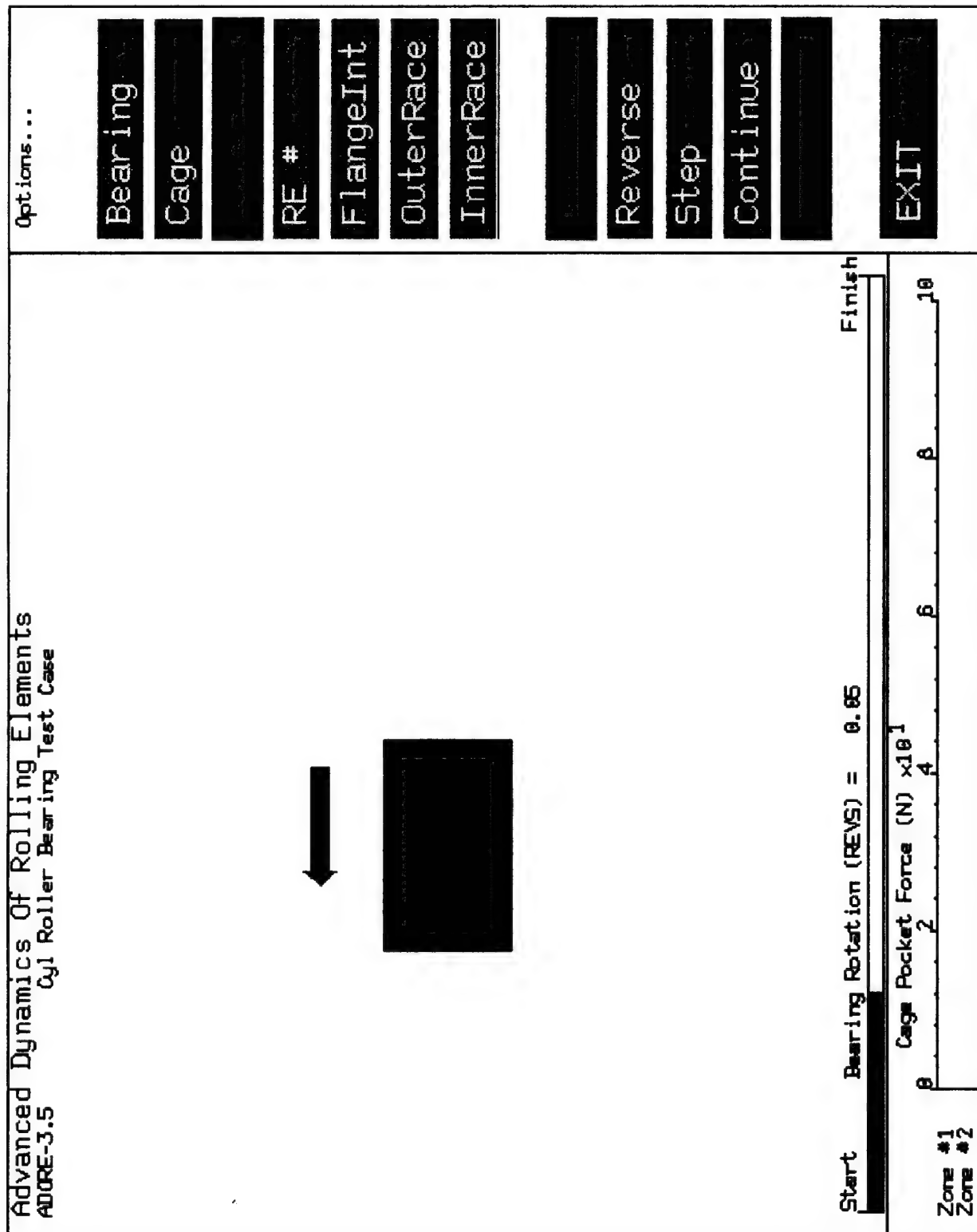
Figure 13b
Typical view of the roller pocket structure.
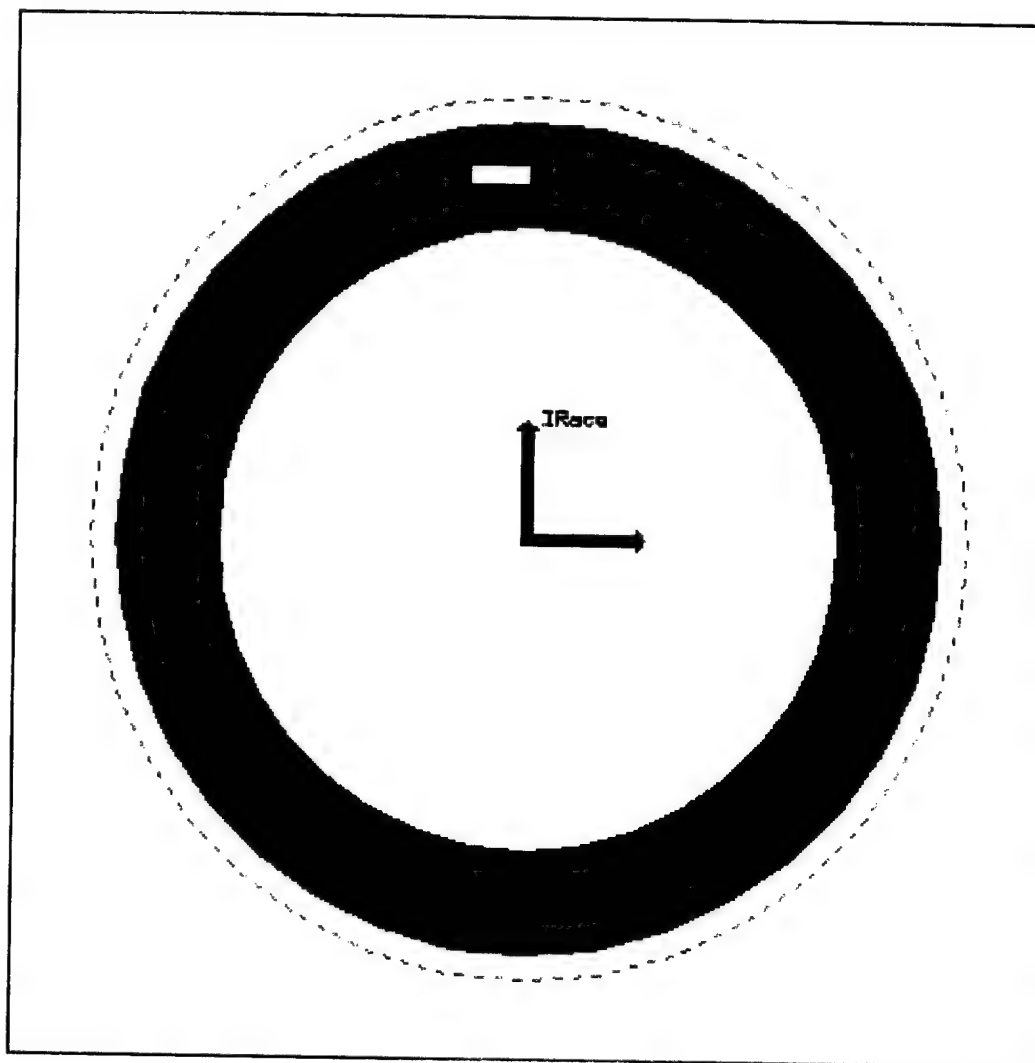
Figure 14
Race structure based on 2-D polygon fill areas.

A local transformation matrix element is inserted at the top of the structure. This matrix is edited to apply the translational and rotational components of race motion, and thereby produce an animated motion.

3.4.1 Race Motion

The display containing motion of the race is very similar to the 2-D cage motion display. Figure 15 shows a typical motion when the bearing is subjected to a rotating load. Again the displacement of race center is displayed at an amplified scale. The angular and rotational whirl velocities are shown in the data area.

3.5 Composite Bearing View

Figure 16 shows the typical composite bearing view as displayed on the opening screen. This view is really a collection of the base structures, discussed above. After editing the various structures for the pertinent motion, the structures are executed in an open structure to create a composite bearing view. The view is designed to present overall bearing motion. Cage pocket highlighting is on to indicate pocket collisions. The animation may be paused immediately upon observing a collision in cage pocket and then the cage pocket interaction may be opened for the given pocket to view the collision in more detail. the cage and race orbits are drawn in the center of the display at an enlarged scale. Cage to race contact is indicated when the cage element touches the dotted circle drawn around the inner race; this example presents an inner race guided cage. The resulting guide land contact force is displayed in the data area for the two guide lands on either side of the rolling elements. The red arrow, which moves relative to the cage fixed reference frame, indicates the angular location of cage/race contact. The tan area around the outer race denotes the radial load distribution around the bearing. The height or thickness of this polygon fill area set denotes the radial load at a given angular position. For the pure thrust load this thickness will be constant, while certain ellipticity will be seen when a radial load is applied. This ellipticity will rotate with the shaft if the bearing is subjected to a rotating load.

3.6 Input Data Base

All inputs to the graphics model are supplied by the bearing dynamics computer code ADORE. Appropriate modifications to this code were made to generate a data base to contain the following information:

3.6.1 Bearing Geometry Data

The first part of the data set contains the required geometrical data to produce a scaled drawing of the bearing. In addition, other text information, such as program version, bearing specification, etc., are contained in this file, so that this information may be displayed on the bearing animation screens. In more specific terms, the following information is documented in this first part of the data set:

1. ADORE version
2. Bearing specification code
3. Type of units
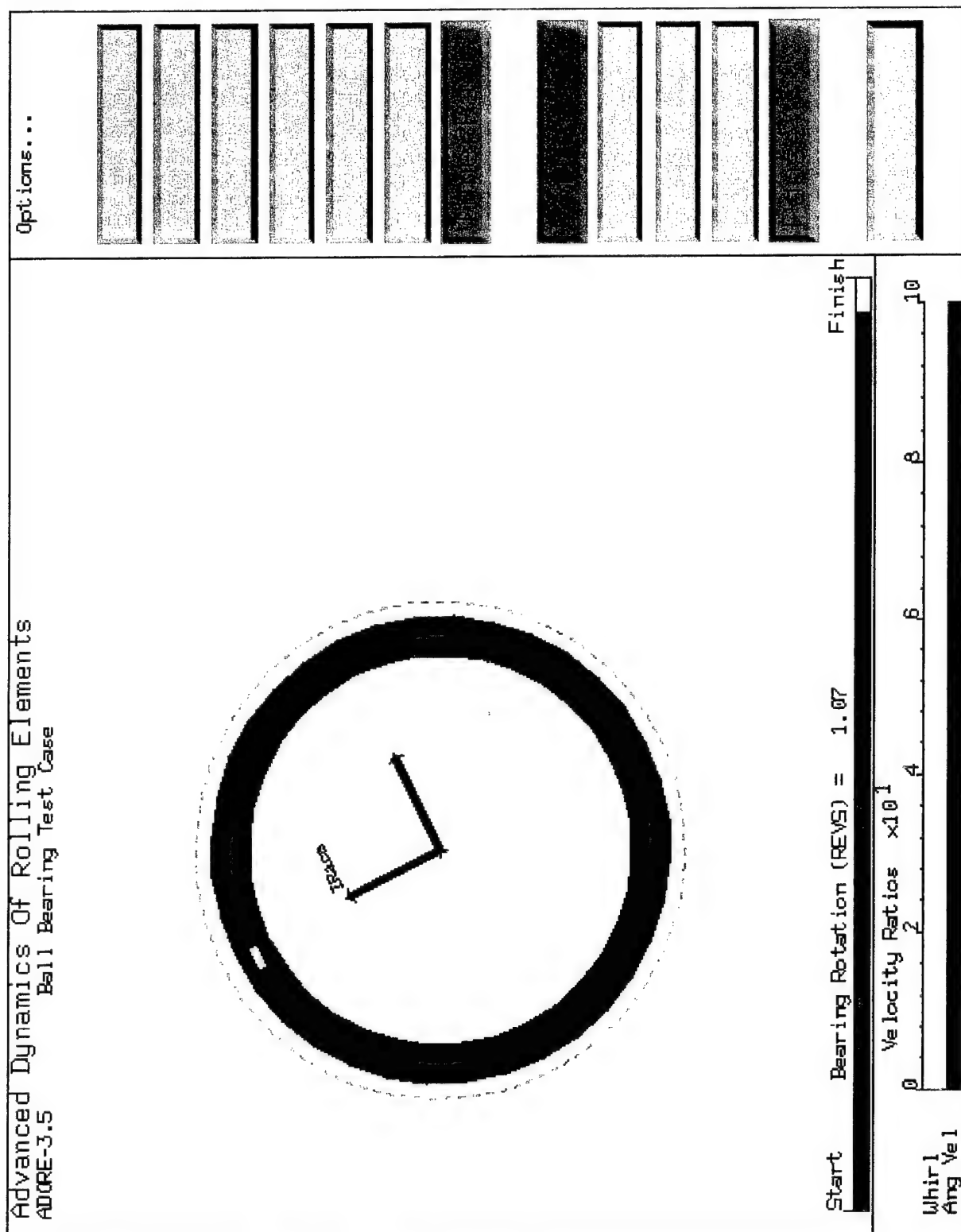
Figure 15
Typical race motion screen.
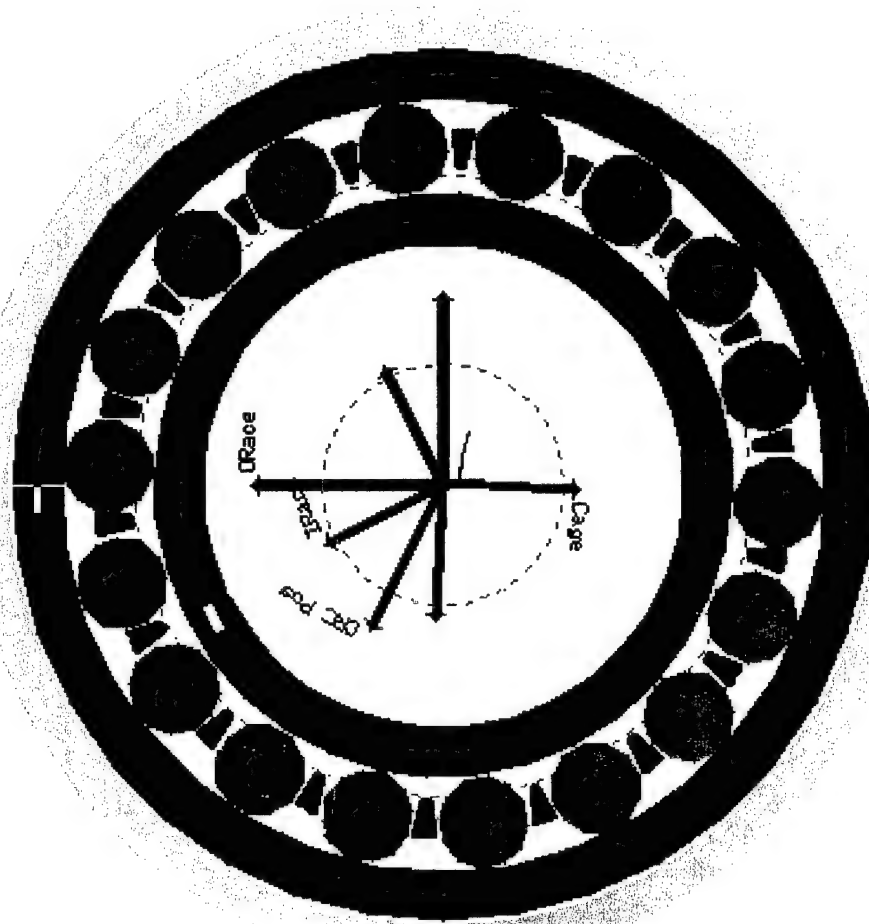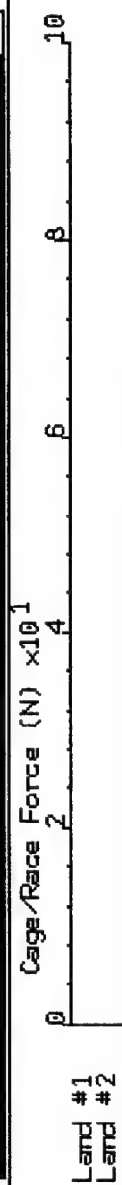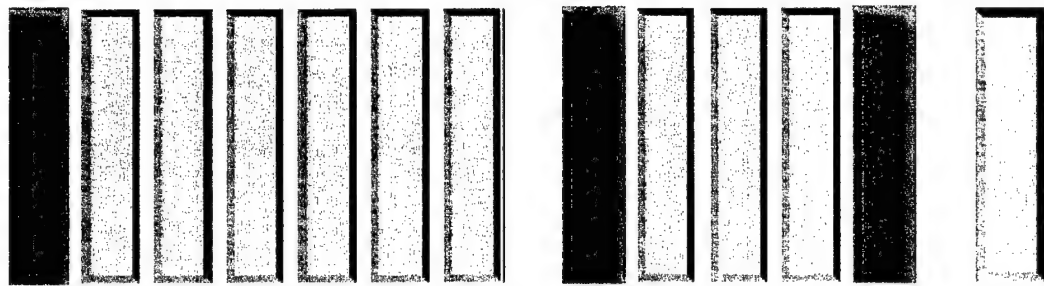
Figure 16
The composite bearing view.

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4. Bearing type
5. Number of rolling elements or balls
6. Number of variables in time-varying solutions
7. Rolling diameter
8. Pitch diameter
9. Race cone angles for tapered roller bearing
10. Guide flange geometry for roller bearings
11. Outer and inner diameters of the two races
12. Outer and inner diameters of the cage
13. Cage pocket and guide land clearances

3.6.2 Time Varying Solutions

Following the above nominal data, the dataset contains the solutions generated by ADORE at each time step. The fundamental coordinates of the bearing elements constitute the main part these solutions. Since ADORE permits all six degrees of freedom for each bearing element, there are six fundamental coordinates which describe the bearing element motion. These solutions are contained in a vector with six components, three coordinates of mass center and the three transformation angles which define the angular orientation of the bearing element. Along with these fundamental coordinates a number of other variables, which are required to produce the animated display are also part of the data record produced at any time step. Following is a summary of contents of ADORE data record generated at each time step:

1. Time step number
2. Value of current time and race rotation
3. Fundamental coordinates for each rolling element, cage and races
4. Contact stress and maximum slip rates at rolling element to race contacts
5. Guide flange contact loads for roller bearing
6. Roller misalignment and skew in roller bearings
7. Cage pockets forces and contact angles in each pocket
8. Rolling element position relative to pocket center in each pocket
9. Cage/Race force and contact angle

Once ADORE execution is completed, this database is attached as an input to the graphics code, AGORE. Since ADORE may be executed with any of the available options, all capabilities of ADORE are seen in the graphics modeling.

4. Typical Animations

To illustrate the results of AGORE for both ball and roller bearing, typical solutions are obtained for three different bearings; an angular contact ball bearing operating in turbine engine environment, a high-speed cylindrical roller bearing typical of small gas turbine application, and a tapered roller bearing operating under hypothetical conditions. Although, it is difficult to appreciate animated motion by a few diagrams, the attempt here is to describe the various views for the three types of bearings.

4.1 Ball Bearing

A 100mm angular contact ball bearing operating at 20,000 rpm with a thrust load of 5,000 N, a rotating radial load of 2,500 N and lubricated with the well known MIL-L-7808 lubricant is considered for the present investigation. This bearing has been used in several past investigations [4-6]. ADORE output at zero time is included in the Appendix. All the bearing geometry, material properties and operating conditions data are documented in this output. ADORE was run over 4,000 time steps to accumulate about 55 shaft revolutions. The program was run on an IBM RS/6000, Model 580 workstation. It took approximate 72 minutes to complete this run. The data set produced by ADORE is input to AGORE to generate the various animated displays. The motions of ball, cage and race are discussed below.

The overall bearing view is shown in figure 17, where all the ball, the cage and races are shown. In the central part of the diagram, radius of the dotted circle is equal to the cage/race guide clearance. When the cage center is outside this circle, there is contact at the guide lands and the resulting forces are seen in the data area. The solid circles close to the dotted circle are cage mass center orbits drawn at an enlarged scale. The arrow labeled as CRC position indicates the angular cage/race contact position. The other two coordinate frames are fixed in the races. As a result of the rotating radial load, the inner race center orbits in a circle relative to the fixed outer race. These orbits are also seen in figure 17 (the solid circles concentric with the cage orbits). The dotted circle around the inner race represents the guide land surface. Whenever the cage touches this circle there is contact between the cage and race. Load variation around the bearing is represented by the shaded area around the bearing. Since the radial load is rotating with the shaft the position of maximum load varies with time. Although not very clear in the figure, there is contact in pockets 10, 14 and 18, as indicated by the highlighted pocket walls.

4.1.1 Ball Motion

Ball race interaction and overall ball motion is shown in figure 18. As the ball travels around the bearing, the contact stress and variations in maximum slip rates in the contact are seen in the main graphics area. Both these quantities are actually drawn to scale, which is indicated on the legend. The solid arrow in the center is along the ball angular velocity vector, while the load lines through the contact stress and slip plots denote the contact angle. The ball whirl and angular velocity variations are seen in the data area.
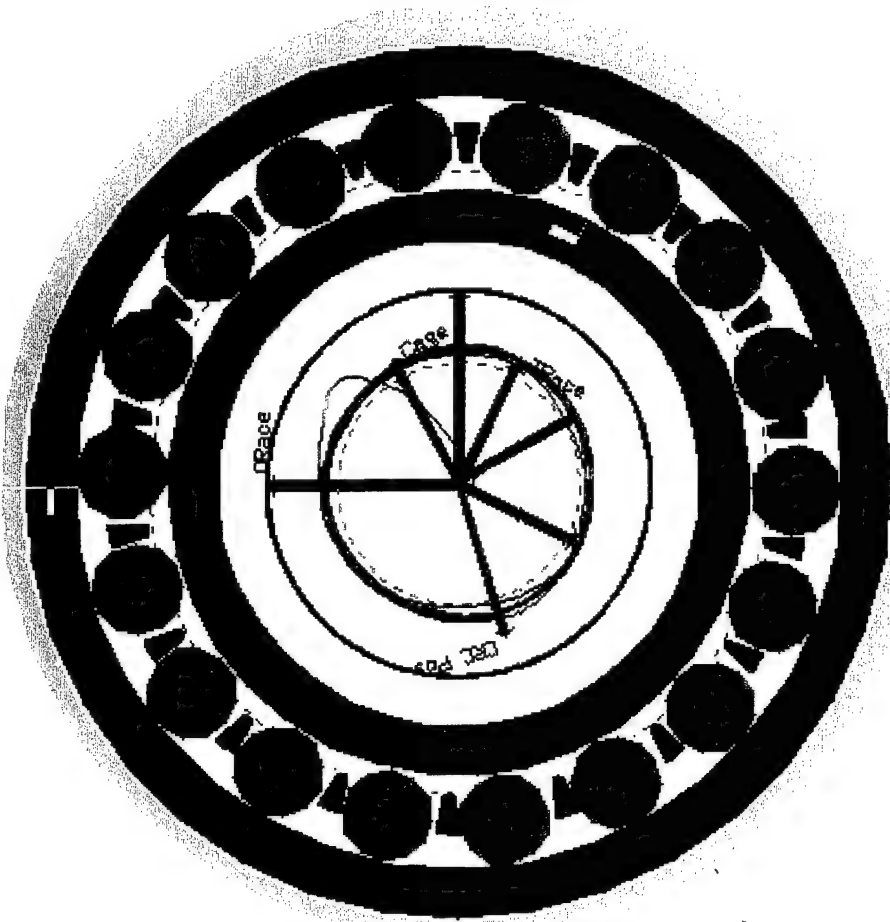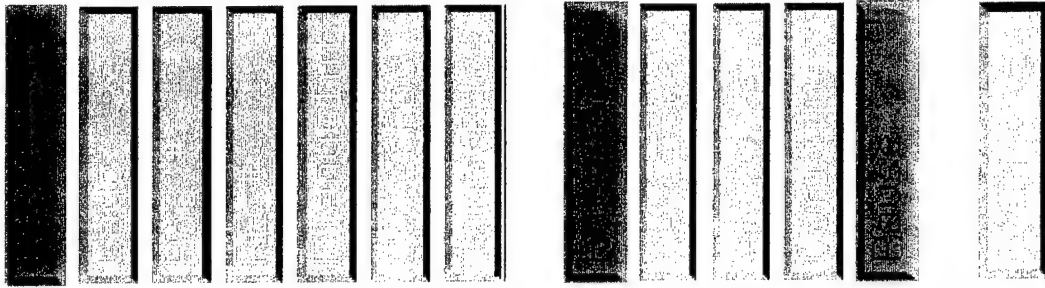
Figure 17

Overall bearing view for the ball bearing example.

30
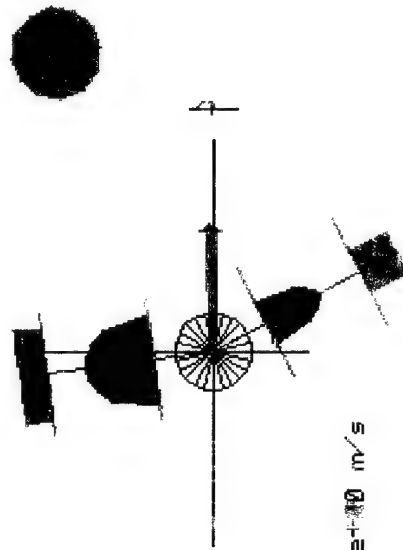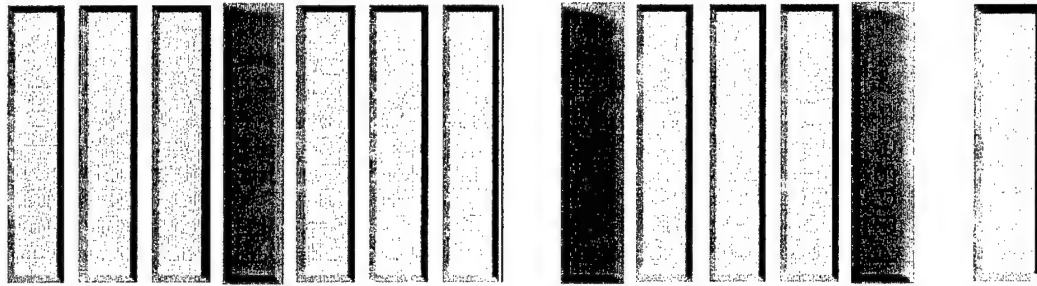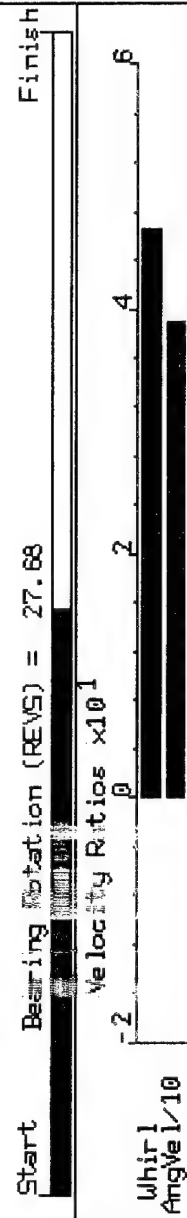
Figure 18

Typical ball motion view for the ball bearing example.

4.1.2 Ball/Cage Interaction

Typical ball cage collision is shown in figure 19 where motion of the ball center is shown relative to cage pocket center. The arrow on the top denotes the rolling direction, while the arrow in the pocket represents the ball/cage contact direction. Magnitude of the contact force is seen in the data area. In figure 19 this force is seen to be about 160 N.

4.1.3 Cage Motions

Motion of the cage in two dimensions in a plane normal to the bearing axis is seen in figure 20. Cage mass center orbits and the clearance circle are plotted on an enlarged scale. Ball/cage contacts are also shown by highlighting the pockets. In figure 20 pockets 10, 14 and 18 are highlighted to indicate contact. Cage angular and whirl velocity ratios are plotted in the data area. Both these ratios are seen to be essentially equal which indicates a fairly stable cage whirl motion.

Three dimensional view of cage motion is shown in figure 21. The whirl orbits are now drawn in a three dimensional space. A small axial and some coning motion, resulting from the combined thrust and radial loads is seen in the animated views. Axial shift of the whirl orbits is indicative of such a motion.

4.1.4 Race Motion

Inner race mass center motion under a combined thrust and rotating radial load is indicated by the solid circle in figure 22. Similar to the cage motion, the race mass center is plotted here at an enlarged scale to demonstrate race whirl. The whirl velocity is of course equal to the angular velocity as seen in the data area.

4.2 Cylindrical Roller Bearing

A small 30mm solid lubricated cylindrical roller bearing with ceramic rollers is considered in the current roller bearing example. The bearing operates at a shaft speed of 70,000 rpm with a fixed radial load of 250 N. Such high speed and light load conditions are typical of small gas turbine applications. This example was run over 1,000 steps to simulate bearing performance over approximately 35 shaft revolutions. At such high speed the time steps in ADORE can be fairly large and, therefore, it took only about 13 minutes of computing effort on the IBM RS/6000 model 850 work station to complete this run. Detailed bearing geometry, material properties and the solutions and step zero are contained in the Appendix. There are only eight rollers in this bearing as seen in the assembled view in figure 23. The shaded area around the bearing now extended over only an arc which implies that only three rollers share the applied radial load. The cage mass center whirl quickly converges to circular orbits after some brief initial transients. In fact, the cage is in almost steady contact with the guiding outer race with a contact force of about 120 N. All other parameters shown in figure 23 are essentially identical to those shown earlier in figure 17 and discussed in the ball bearing example.

4.2.1 Roller Motion

Typical roller motion parameters are shown in figure 24. The contact angles are of course zero for the radially loaded cylindrical roller bearing. Contact stress and slip rate profiles are dis-
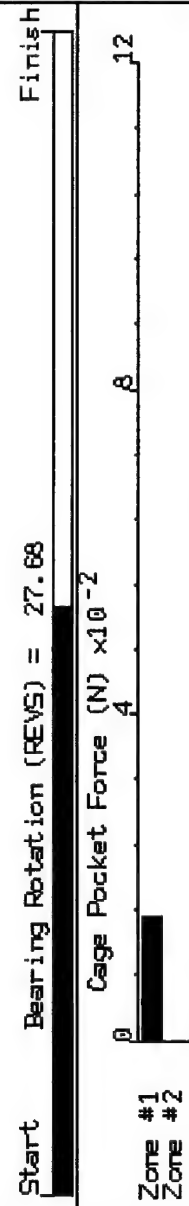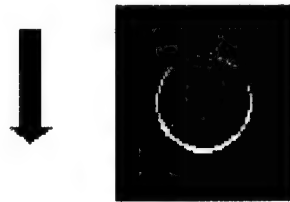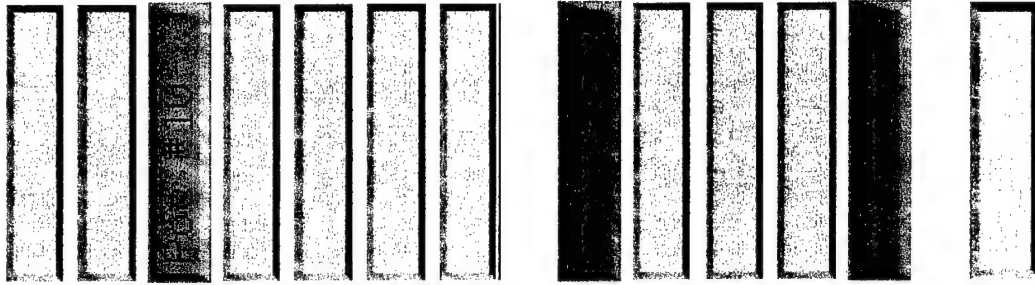
Figure 19
Typical ball/cage interaction.
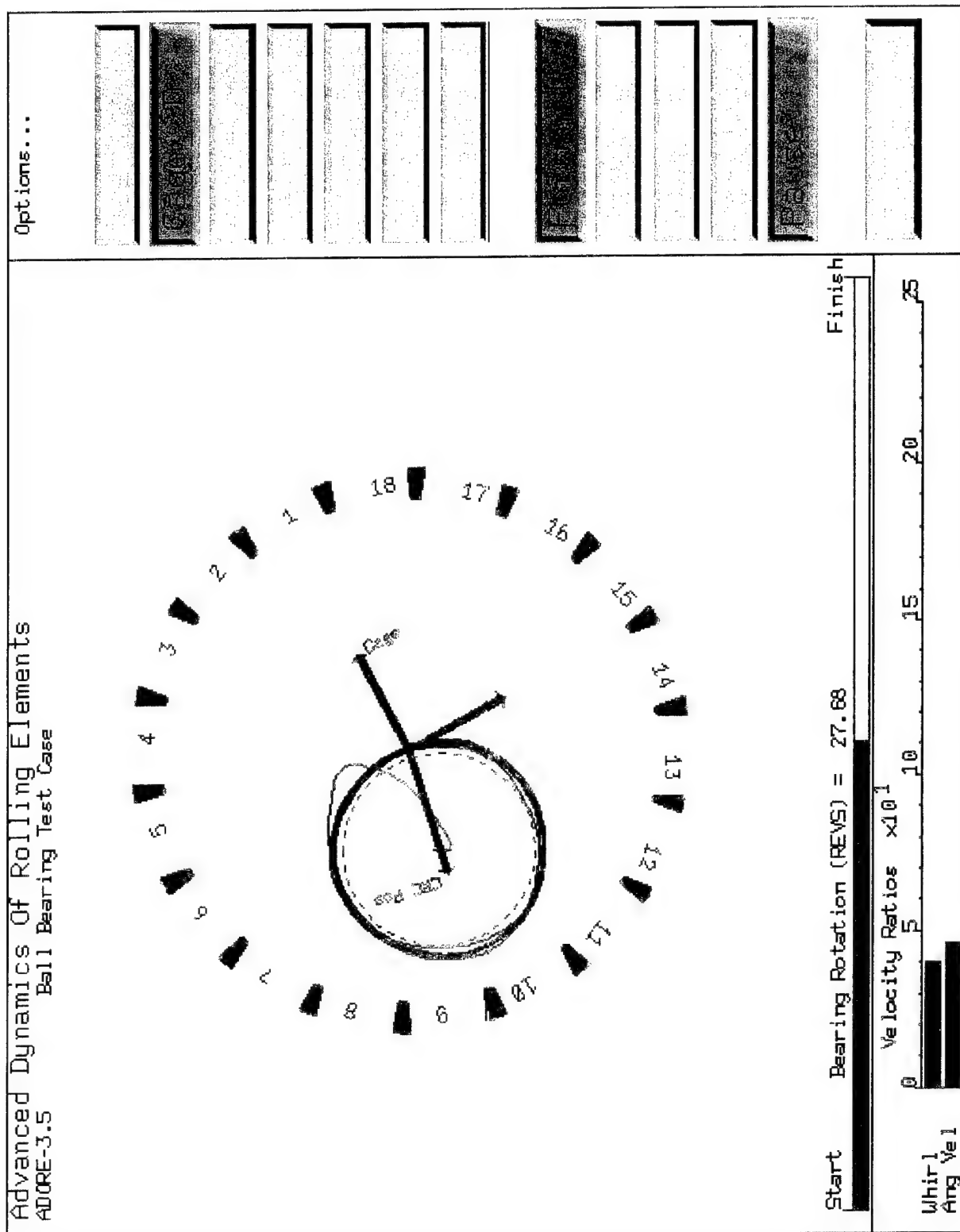
Figure 20
2-D cage motion display for the ball bearing example.
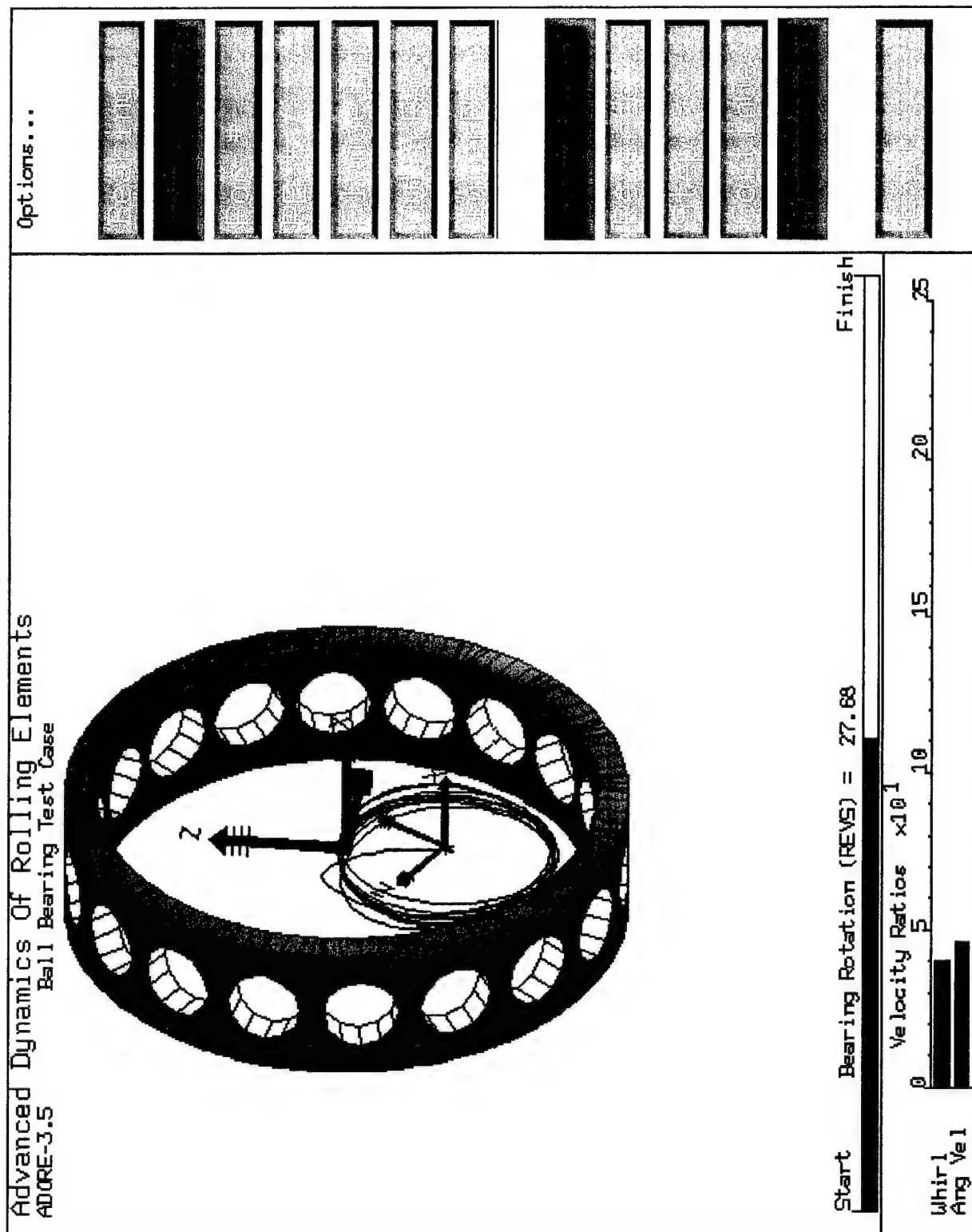
Figure 21
Typical 3-D cage view for the ball bearing example.
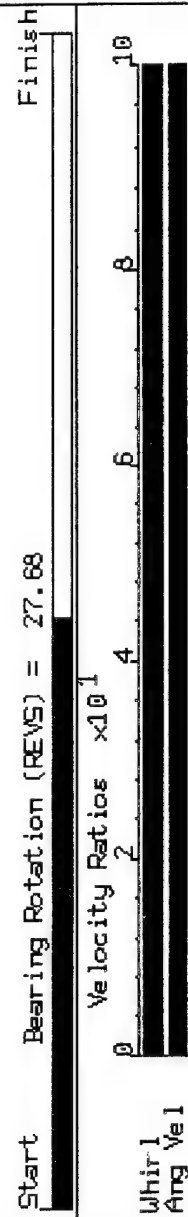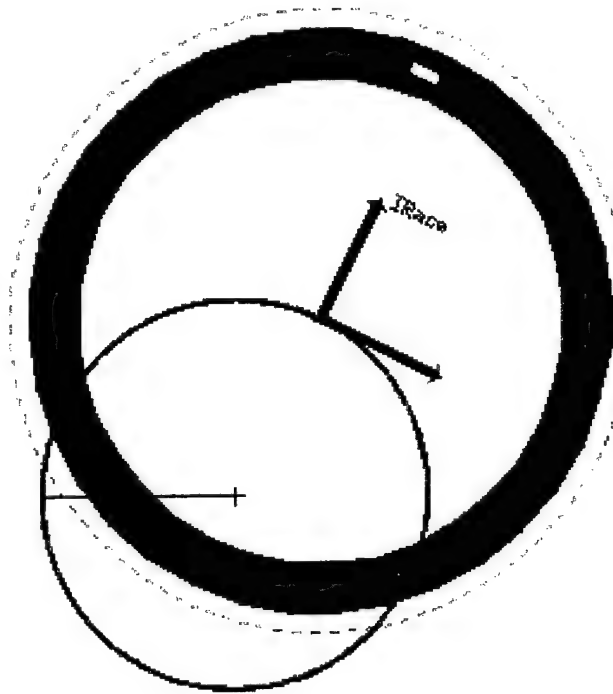
Figure 22

Motion of the orbiting inner race under a rotating load.

Figure 23

Assembled view for the cylindrical roller bearing example.

37
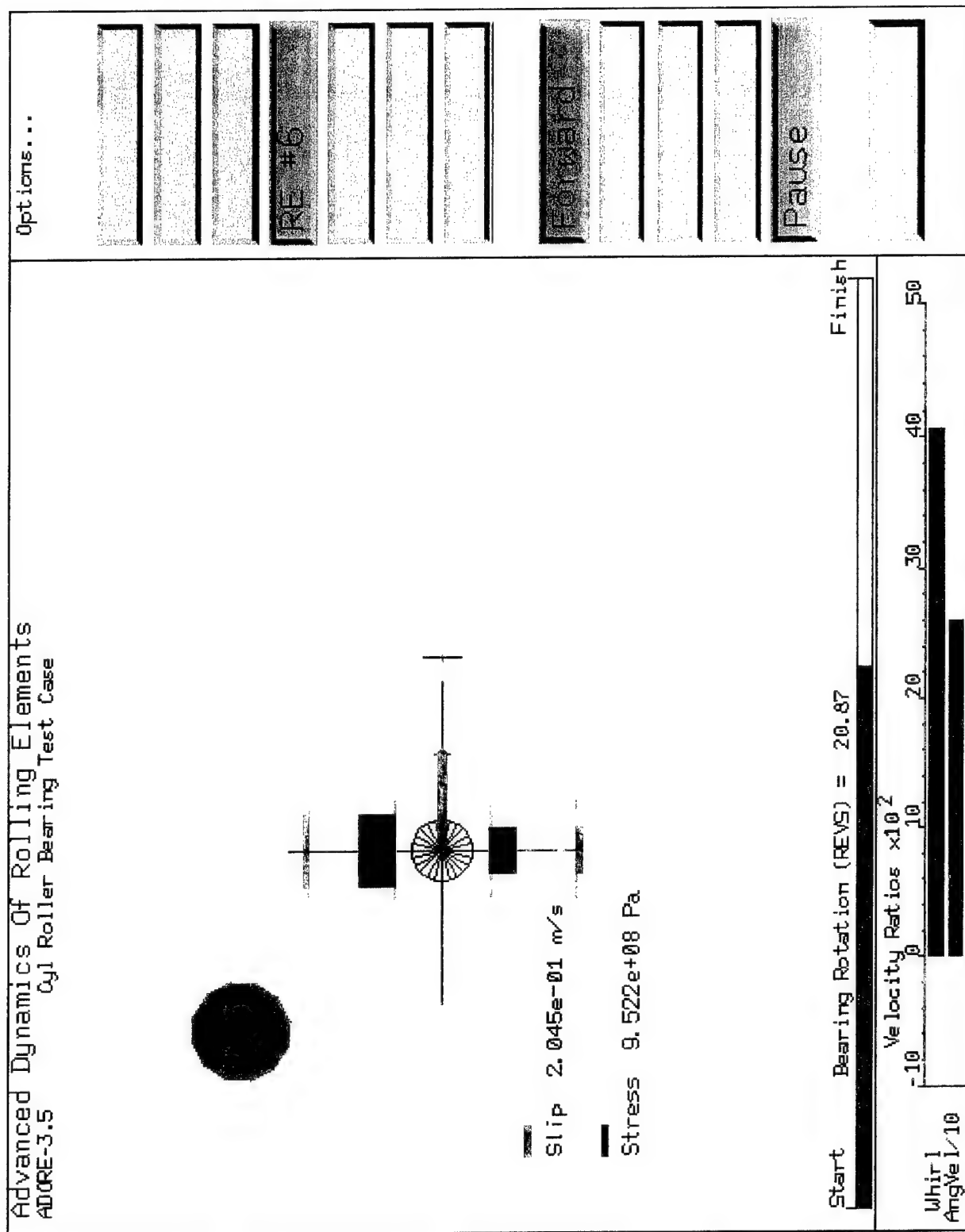
Figure 24

Typical roller motion screen for the cylindrical roller bearing example.

played in the main graphics area, while the roller orbital and angular velocities are plotted in the data area. Clearly, this display is very similar to that shown earlier in figure 18 for the angular contact ball bearing.

4.2.2 Roller/Flange Contacts

Roller/flange interaction display is shown in figure 25. However, under a pure radial load and no geometrical imperfections on the rollers there is no source for roller misalignment and/or skew. Therefore, there is really no interaction between the roller corners and the guide flanges. The display in figure 25 just demonstrate the different parts of this display. In the top part the contact configuration is generally displayed. Roller position between the two guide rails on the race is shown in the lower part of the diagram. If the roller skews, the skew angle will be seen in this profile. The contact load distribution on the race is also included in the display. For the present bearing, as seen in figure 25, the contact zone extends from about -60 to +60 degrees.

4.2.3 Roller/Cage Interaction

Motion of the roller in the cage pocket is displayed in figure 26. Again, if the roller skews, it will appear as tilted in this display. In the present example there is neither misalignment nor skew. Therefore, contact between the roller and cage pocket is quite uniform, as seen in figure 26. The direction on contact force on the roller is shown by the arrow in the pocket, while the arrow on the top indicates the rolling direction. Magnitude of the contact force, approximately 4 N in the present example, is displayed in the data area.

4.2.4 Cage Motion

Whirl motion of the cage in a two dimensional plane, normal to the bearing axis, is shown in figure 27. Again, similar to the ball bearing, the cage whirl orbits are drawn to an enlarged scale and whenever the roller hits the pocket, color of the pocket surface is changed to highlight the particular pocket. In figure 27, pocket #5 is highlighted to indicate roller/cage contact. Cage whirl and angular velocity ratios are shown in the data area. A stable cage whirl is indicated by the fact that the whirl velocity is essentially equal to the angular velocity. Such a result was also seen earlier in figure 20 in the ball bearing example.

Cage motion in a three dimensional space is displayed in figure 28. For all roller bearings the cage pocket is always shown to be rectangular, although ADORE may permit fairly sophisticated shapes. The cage geometry in AGORE should, therefore, be viewed only in a schematic sense. The cage whirl orbits essentially lie on top of each other, which implies a planner motion. This would, of course, be expected since there is no misalignment or skew in the bearing.

4.3 Tapered Roller Bearing

A hypothetical tapered roller bearing operating under combined thrust and radial load is considered as an example to demonstrate AGORE output for tapered roller bearing. Both the bearing geometry and operating conditions are truly hypothetical and they do not represent any practical application. The output included in the Appendix describes the geometry and operating conditions. The bearing operates at 2,500 rpm with a thrust load of 5,000 N and a stationary radial load of 500 N. The bearing is assumed to be lubricated with an SAE 30 type lubricant. ADORE
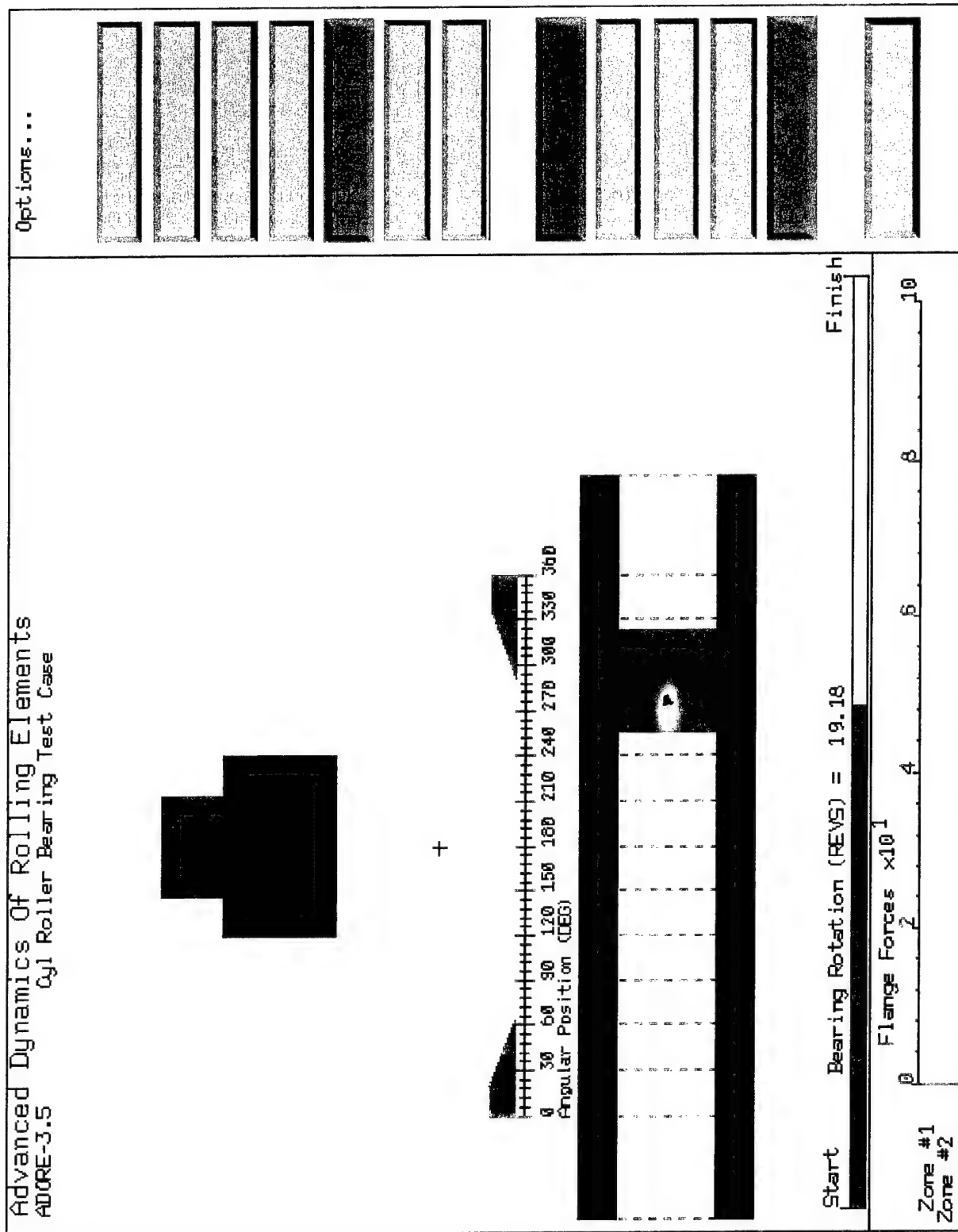
Figure 25

Roller/flange interaction view for the cylindrical roller bearing.
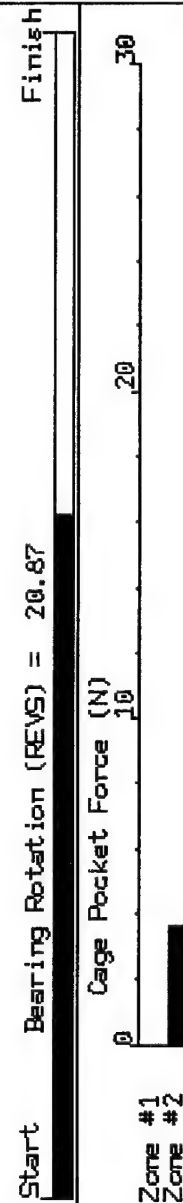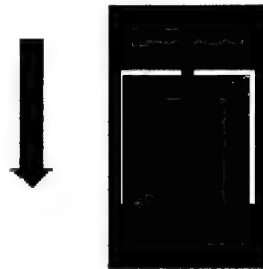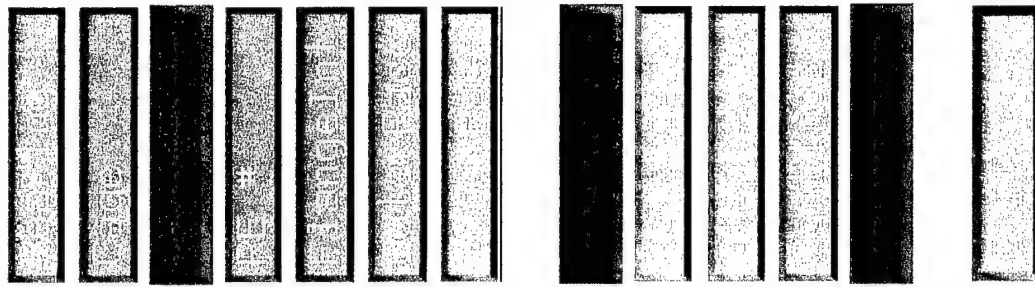
Figure 26

Typical cage pocket interaction in cylindrical roller bearing.
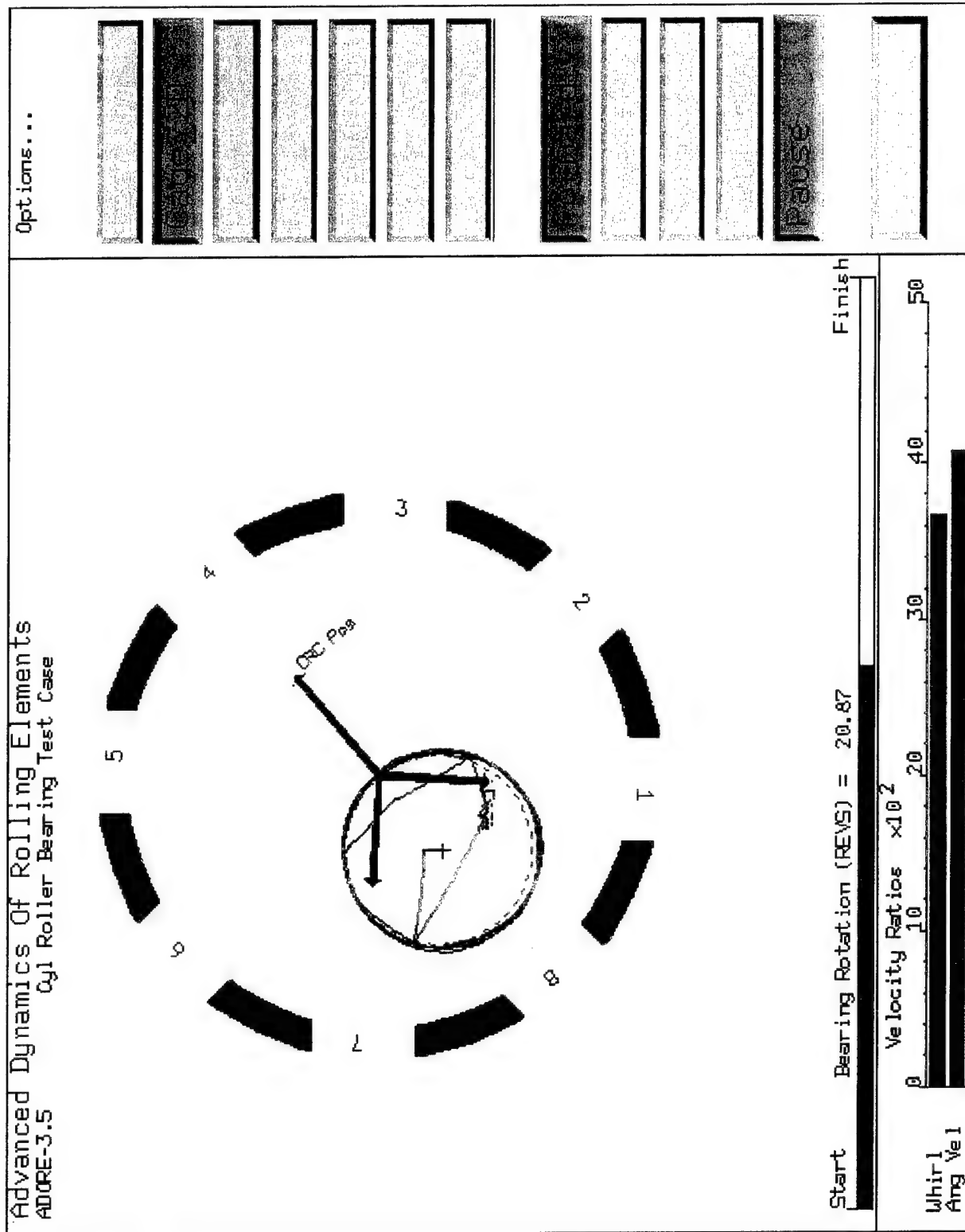
Figure 27
2-D cage motion for the cylindrical roller bearing.

Figure 28

3-D cage motion for the cylindrical roller bearing example.

was run over 4,000 steps to simulate bearing performance over about two revolutions. This run took about 3 hours of computer time on the IBM RS/6000, model 580 work station. Interactions are tapered roller bearings are, in general, quite complicated since the roller always goes through misalignment and skew. Even when, there is not external misalignment, the gyroscopic moment of the roller results in some misalignment and skew. The required computing effort is relatively large, primarily due to such complexities in the roller motion.

Figure 29 shows the two dimensional bearing view, which is quite similar to those seen earlier for the ball and cylindrical roller bearings. Variation in load around the bearing is quite small (thrust to radial load ratio is 10) and it is hardly visible in the plotted load area in figure 29. The cage simply moves up and down and there is no whirl. Similar to the ball and cylindrical roller baring example, the data area contains the force variations at the cage/race contact. In the selected bearing, there is only one guide land. Therefore, the data plot is significant only for one of the guide lands, #2 in the present example.

4.3.1 Roller Motion

Figure 30 shows the roller motion parameters. Roller/race contact stress and slip rates are displayed as the roller travels around the bearing. At the large applied thrust to radial load ratio, the variation in applied load around the bearing is quite small. Both translational and angular acceleration of the roller are other sources which lead to some variation in roller motion parameters. These variations, although small, are seen in the animated view corresponding to figure 30. The overall roller orbital and angular velocities are essentially constant.

4.3.2 Roller/Flange Contact

Roller interaction at the guide flange is displayed in figure 31. Primarily due to acceleration of the roller there is some variation in roller flange load, which corresponds to the dynamic variation in roller/race load as seen in figure 31. Average flange force, however, is basically constant.

4.3.3 Cage Motion

As mentioned earlier, the cage pockets in all bearings are drawn as rectangular, although the geometry in ADORE may be significantly more complicated. In fact, tapered bearing pockets are not rectangular at all. In the present example the pocket walls are actually tapered and they conform to the roller taper angle. Cage pocket displays, as shown in figure 32, should therefore be only viewed in a schematic sense. The orientation of the roller relative to the nominal pocket geometry indicates roller skew as it travels around the bearing. Pocket forces as the roller collides in the pocket are displayed in the data area.

Cage motion in a plane normal to the bearing axis is displayed in figure 33. As discussed above, the cage just moves up and down radially in a somewhat erratic fashion and there is no well defined whirl. Cage pockets are highlighted in this view to indicate roller/cage contacts. In figure 33, pockets 2, 3 and 4 are highlighted. Cage angular and whirl velocity ratios are plotted in the data area. There is some coning motion of the cage primarily resulting from roller skew; this may be appreciated in the three dimensional view of the cage, as shown in figure 34.
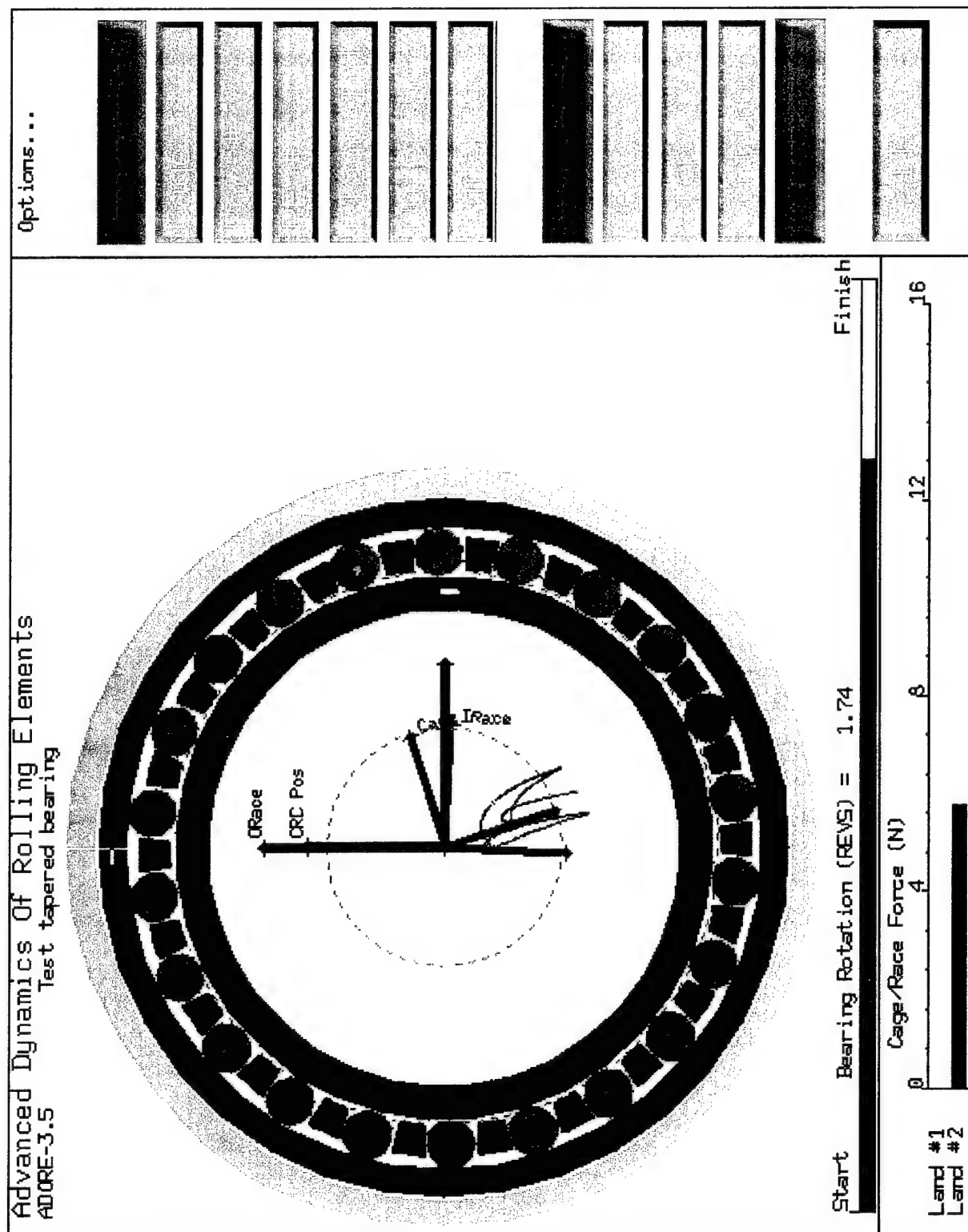
Figure 29

Composite bearing view for the tapered roller bearing example.
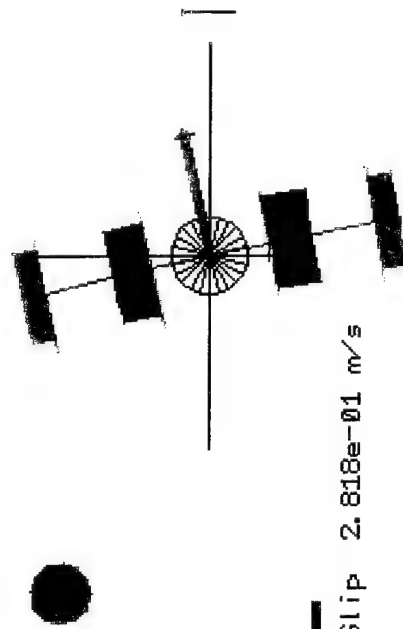
Figure 30

Typical roller motion parameters for the tapered roller bearing.
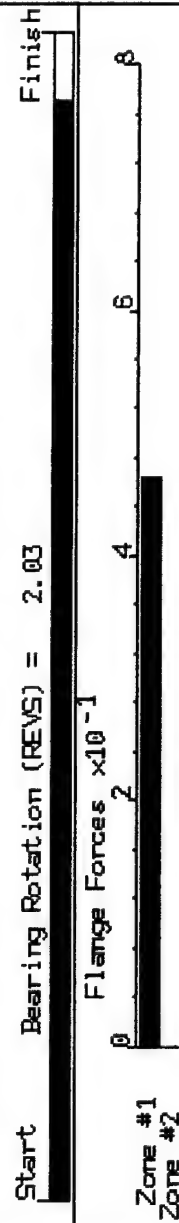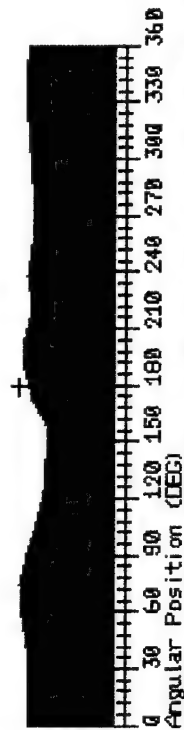
Figure 31

Typical guide flange interaction in the tapered roller bearing example.
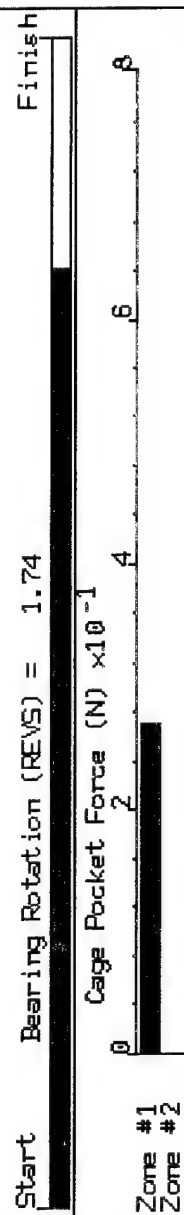
Figure 32

Schematic of roller/cage interaction for the tapered roller baring example.
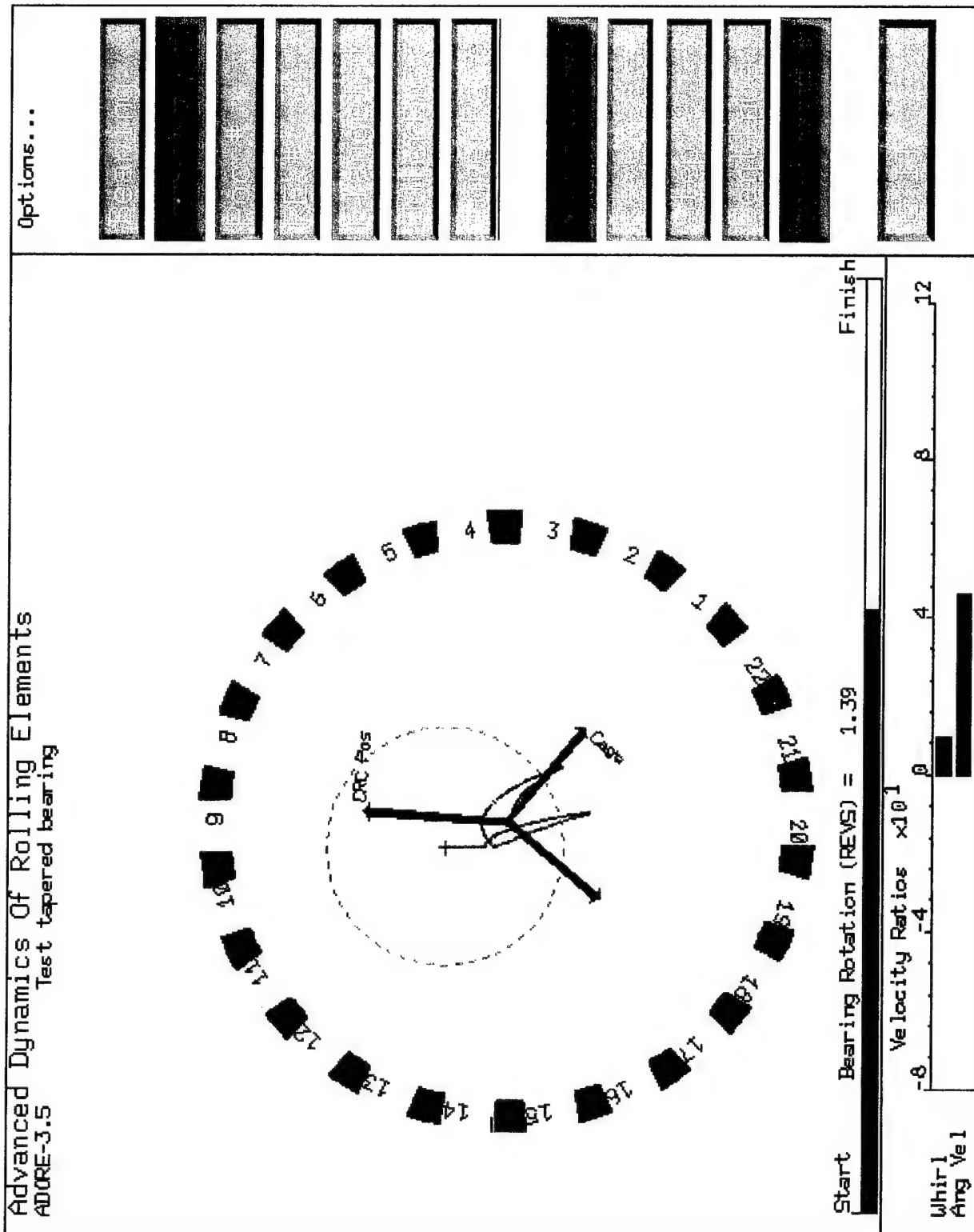
Figure 33
2-D view of cage motion in the tapered roller bearing.

Figure 34

3-D view of cage motion in the tapered roller bearing example.
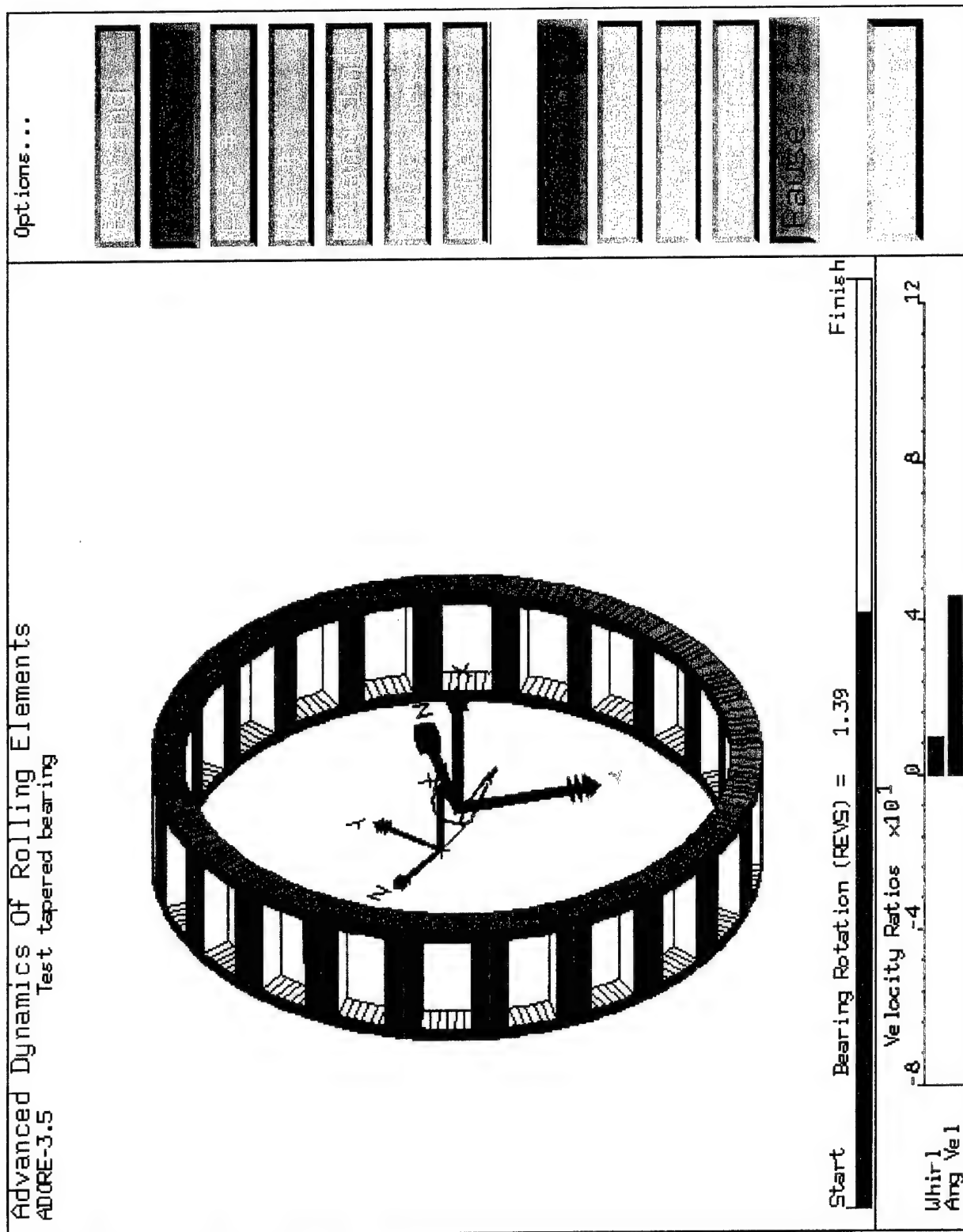
5. Conclusions

Significant insight into the most complex motion of the elements of rolling bearings may be obtained by animated views of the motion and various interactions in the bearing. While the components of motion are obtained by integrating the classical differential equations of motion, the animated views are generated by applying appropriate transformations on the graphics structures based on the ISO/PHIGS standards. The modeling capabilities are demonstrated in the present project by interfacing the graphics development with existing bearing dynamics models. An existing bearing dynamics computer code, ADORE is used to solve for the components of dynamic motion. The standard PHIGS libraries are used to develop a graphics code, Animated Graphics Of Rolling Elements (AGORE). By editing the graphics structures in this model with the transformations based on the motion computed by ADORE, animated view of bearing motion may be produced. Hardware capabilities, such as double buffering and z-buffers are necessary to produce a smooth picture. An IBM RS/6000 workstation, operating in the Unix environment, is found to have adequate capabilities, both in terms of computing speed and graphics processing. The integrated software-hardware prototype system in the present investigation is, therefore, based on this type of workstation. Since the Unix operating system and the PHIGS procedures are basically standardized, the graphics model developed herein, can be easily ported to any unix based computer system.

6. References

1. Gupta, P.K., "Animated Computer Graphics Modeling of Rolling Bearing Dynamics," SBIR Phase I Technical Report, G-112-TR, Air Force Contract F33615-91-C-2132, Aero Propulsion and Power Directorate, Wright-Patterson Air Force Base, Ohio, October 1991.

2. Gupta, P.K., ADVANCED DYNAMICS OF ROLLING ELEMENTS, Springer-Verlag, New York, 1984.

3. Foley, J.D., van Dam, A., Feiner, S.K. and Hughes, J.F., COMPUTER GRAPHICS - PRINCIPLES AND PRACTICE, 2nd Edition, Addison Wesley, 1990.

4. Gupta, P.K., "On the Geometrical Imperfections in Ball Bearings," J. of Tribology, ASME Trans, Vol 110F, pp 13-18, 1988.

5. Gupta, P.K., Dill, J.F., Artuso, J.W. and Forster, N.H., "Ball Bearing Response to Cage Unbalance," J. of Tribology, ASME Trans, Vol 108F, pp 462-467, 1986.

6. Gupta, P.K., "Visco-Elastic Effects in MIL-L-7808 Type Lubricant - Part III: Model Implementation in Bearing Dynamics Computer Code," Presented at 1991 STLE Annual Meeting, Montreal, Canada. To be published in STLE Tribology Transactions.

Appendix
ADORE Print Output

Ball Bearing Test Case

The ball bearing case consist of a 100 mm angular contact ball operating under a thrust load of 5,000 N and a rotating radial load of 2,000 N at a shaft speed of 20,000 rpm. The bearing is lubricated with the MIL-L-7808 type lubricant. The ouput presented below contains details of the bearing geometry, material properties, operating conditions, and the initial conditions which correspond to a quasi-static equilibrium solution.

```
    LISTING OF INPUT DATA RECORDS ---
    *****************************

Rec 1              1     0     0     9    500     2     0  4000      5
Rec 2.1       5.0000E-02 5.0000E-03 3.0000E-01 1.0000E+03 1.0000E-04 0.0000E+00
Rec 3.1       Ball Bearing Test Case
Rec 3.2         2  1  0  0 18  0  0  0  0
Rec 3.3         0  1  0  0  3  0  0  0  0  2
Rec 3.4         0  1  0  0  1  2  1 13
Rec 4.1       1.0000E-01 1.8000E-01 2.0000E-02 2.0500E-01 3.0000E-02 3.0000E-02 1.0000E-05 5.0000E-05
Rec 4.2       3.2300E+02 3.2300E+02 3.2300E+02 3.2300E+02 3.2300E+02 3.2300E+02
Rec 5A        1.9050E-02 1.4000E-01 2.5000E+01 5.2000E-01 5.4000E-01
Rec 7.0         0  0  0  2  2  0  0  0  0
Rec 7.1       1.4629E-01 1.3007E-01 3.6241E-02 4.7358E-03 1.4605E-03 0.0000E+00 0.0000E+00
Rec 7.2.1     1.3007E-01 8.0000E-03 1.8120E-02 1.4605E-03
Rec 7.2.2     1.3007E-01 8.0000E-03 1.8120E-02 1.4605E-03
Rec 7.3       8.6360E-04 0.0000E+00 6.6360E-04 3.2300E+02 0.0000E+00 0.0000E+00-1.0000E-04 0.0000E+00 0.0000E+00 0.0000E+00
Rec 9.1.1     5.0000E+03 0.0000E+00 2.0000E+03 0.0000E+00 0.0000E+00 0.0000E+00
Rec 9.1.2     0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 2.0000E+04
Rec 9.3       0.0000E+00 1.0000E+00 0.0000E+00 2.0000E+04
Rec 10.1      0.0000E+00 2.0000E-02 1.6000E-02 1.0000E+00
Rec 10.3      1.2500E-07 1.0000E+01
Rec 10.5.1    5.0000E-02 0.0000E+00 0.0000E+00-5.0000E-02 5.0000E-07
Rec 10.5.2    5.0000E-02 0.0000E+00 0.0000E+00-5.0000E-02 5.0000E-07
Rec 11        0.0000E+00 0.0000E+00-9.8100E+00


    INPUT FROM USER ACCESSIBLE ROUTINES ---
    ***********************************
```

```
AAAAAAAAA    DDDDDDDDD    OOOOOOOO    RRRRRRRRR    EEEEEEEEEE
AAAAAAAAAA   DDDDDDDDDD   OOOOOOOOOO  RRRRRRRRRR   EEEEEEEEEE
AA      AA   DD      DD   OO      OO  RR     RR    EE
AA      AA   DD      DD   OO      OO  RR     RR    EE
AA      AA   DD      DD   OO      OO  RRRRRRRRR    EEEEEE
AA      AA   DD      DD   OO      OO  RRRRRRRR     EEEEEE
AAAAAAAAAA   DD      DD   OO      OO  RR RR        EE
AAAAAAAAAA   DD      DD   OO      OO  RR  RR       EE
AA      AA   DDDDDDDDDD   OOOOOOOOOO  RR   RR      EEEEEEEEEE
AA      AA   DDDDDDDDD    OOOOOOOO    RR   RR      EEEEEEEEEE

ADVANCED       DYNAMICS       OF     ROLLING       ELEMENTS
========       ========       ==     =======       ========
```

-A REAL TIME SIMULATION OF ROLLING BEARING PERFORMANCE-
(VERSION ADORE-3.5)

COPYRIGHT
PRADEEP K GUPTA INC

****
*   *
*   BEARING TYPE = BALL   PROGRAM MODE = 1   SPEC CODE = Ball Bearing Test Case   *
*   *
****

BEARING GEOMETRY

NO OF BALLS	18	OUTER CUR FAC	5.20000E-01	OUTER FIT	(M) 1.00000E-05	SHAFT OD	(M) 1.00000E-01
BALL DIA	(M) 1.90500E-02	INNER CUR FAC	5.40000E-01	INNER FIT	(M) 5.00000E-05	SHAFT ID	(M) 2.00000E-02
PITCH DIA	(M) 1.40000E-01	DIA PLAY	(M) 2.14180E-04			BEARING OD	(M) 1.80000E-01
CON ANGLE (DEG) 2.50000E+01		END PLAY	(M) 9.66105E-04			HOUSING OD	(M) 2.05000E-01
						WIDTH I	(M) 3.00000E-02
						WIDTH II	(M) 3.00000E-02

CAGE OD	(M) 1.46292E-01	CAGE WIDTH	(M) 3.62410E-02	LAND DIA	(M) 1.30073E-01	LAND WIDTH	(M) 8.00000E-03
CAGE ID	(M) 1.30073E-01	POC CLS I	(M) 8.63600E-04		1.30073E-01		8.00000E-03
OUTER CLS	(M) 4.73583E-03	POC CLS II	(M) 0.00000E+00	LAND CLS	(M) 1.46050E-03	LAND POS	(M) 1.81204E-02
INNER CLS	(M) 1.46050E-03	POCKET SHAPE	0		1.46050E-03		1.81204E-02
GUIDE LAND TYPE 2	2						

MATERIAL PROPERTIES

		ROLLING ELEMENT	OUTER RACE	INNER RACE	CAGE	SHAFT	HOUSING
DENSITY	(KGM/M**3)	7.75037E+03	7.75037E+03	7.75037E+03	7.75037E+03	7.75037E+03	7.75037E+03
ELASTIC MODULUS	(PA)	1.99948E+11	1.99948E+11	1.99948E+11	1.99948E+11	1.99948E+11	1.99948E+11
POISSON-S RATIO		2.50000E-01	2.50000E-01	2.50000E-01	2.50000E-01	2.50000E-01	2.50000E-01
COEFF OF THERMAL EXP	(1/K)	1.17000E-05	1.17000E-05	1.17000E-05	1.80000E-05	1.17000E-05	1.17000E-05
HEAT CAPACITY	(N*M/KGM/K)	4.70000E+02	4.70000E+02	4.70000E+02	4.70000E+02		
THERMAL CONDUCTIVITY	(N/S/K)	4.30000E+01	4.30000E+01	4.30000E+01	4.30000E+01		
ELASTIC STRAIN LIMIT		2.00000E-03	2.00000E-03	2.00000E-03	2.00000E-03		
HARDNESS	(RC)	6.10000E+01	6.10000E+01	6.10000E+01	2.00000E+01		
WEAR COEFFICIENT		5.00000E-06	5.00000E-06	5.00000E-06	5.00000E-04		

INERTIAL PARAMETERS

	......MASS (KGM)	..........MOMENT OF INERTIA.......... (KGM*M**2)			..........MASS TO GEO CENTER.......... (M)		
		X-COMP	Y-COMP	Z-COMP	X-COMP	Y-COMP	Z-COMP
RE	2.80547E-02	1.01811E-06	1.01811E-06	1.01811E-06	0.00000E+00	0.00000E+00	0.00000E+00
CAGE	6.36472E-01	3.04873E-03	1.59403E-03	1.59403E-03	0.00000E+00	0.00000E+00	0.00000E+00

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```
         .........PRINCIPAL TO GEO FRAME........
                         (DEG)
                X-COMP      Y-COMP      Z-COMP


    RE  0.00000E+00  0.00000E+00  0.00000E+00
  CAGE  0.00000E+00  0.00000E+00  0.00000E+00
```

LUBRICATION PARAMETERS

	CRITICAL FILM (M)	TRAC COEFF AT ZERO SLIP	MAXIMUM TRAC COEFF	TRAC COEFF AT INF SLIP	SLIP AT MAX TRACTION (M/S)	COEFFICIENT A	COEFFICIENT B (S/M)	COEFFICIENT C (S/M)	COEFFICIENT D
RE/RACE	1.25000E-07	0.00000E+00	2.00000E-02	1.60000E-02	1.00000E+00				
RE/CAGE	5.00000E-07					5.00000E-02	0.00000E+00	0.00000E+00	-5.00000E-02
CAGE/RACE	5.00000E-07					5.00000E-02	0.00000E+00	0.00000E+00	-5.00000E-02

LUBRICANT CODE..... 3 MIL-L-7808

	REF TEMP (K)	VISCOSITY (PA*S)	PR-VIS COEFFICIENT (1/PA)	TEMP-VIS COEFF TYPE 1 (1/K)	TEMP-VIS COEFF TYPE 2 (K)	THERMAL CONDUCTIVITY (N/S/K)	STARVATION PARAMETER	REF ROLLING VELOCITY (M/S)
LUB FILM	3.23000E+02	8.61600E-03	1.07562E-08		2.96433E+03	9.65790E-02	1.00000E+01	
TRACTION	3.23000E+02	8.08061E-02	5.22140E-09	4.22300E-02				2.54000E+01

FATIGUE PARAMETERS

	FATIGUE CONSTANTS POINT CONTACT (N/M**1.80)	FATIGUE CONSTANTS LINE CONTACT (N/M**(50/27))	LOAD EXPONENTS POINT CONT	LOAD EXPONENTS LINE CONT	LIFE MULTIPLIERS MAT MATRIX	LIFE MULTIPLIERS SUR DEFECTS	WEIBULL DISPERSION EXPONENT
OUTER RACE	1.87431E+07	1.66550E+08	3.00000E+00	4.00000E+00	1.00000E+00	1.00000E+00	1.11111E+00
INNER RACE	1.87431E+07	1.66550E+08	3.00000E+00	4.00000E+00	1.00000E+00	1.00000E+00	1.11111E+00

	COMPOSITE RMS ASPERITY HEIGHT (M)	COMPOSITE RMS ASPERITY SLOPE (RAD)	EFFECTIVE HARDNESS (RC)	PLASTIC SHEAR STRESS LIMIT (PA)	ASPERITY TRACTION COEFFICIENT	EMPERICAL SURFACE HAZARD CONSTANT	
							BEARING WEIBULL SLOPE 1.11111E+00
							LIFE MODIFICATION CODE 2
OUTER RACE	1.00000E-07	2.00000E-02	6.10000E+01	2.47997E+08	1.20000E-01	3.70508E+00	
INNER RACE	1.00000E-07	2.00000E-02	6.10000E+01	2.47997E+08	1.20000E-01	3.70508E+00	

INITIAL OPERATING CONDITIONS

Ball Bearing Test Case

			OUTER RACE	INNER RACE
ROOM TEMPERATURE	(K)	3.23000E+02		
HOUSING TEMPERATURE	(K)	3.23000E+02		
SHAFT TEMPERATURE	(K)	3.23000E+02		
ROLLING ELEMENT TEMPERATURE	(K)	3.23000E+02		
CAGE TEMPERATURE	(K)	3.23000E+02		

```
                                                        OUTER RACE    INNER RACE

ANGULAR VELOCITY         (RPM)  0.00000E+00  2.00000E+04
TEMPERATURE              (K)    3.23000E+02  3.23000E+02
MISALIGNMENT-Y           (RAD)  0.00000E+00  0.00000E+00
MISALIGNMENT-Z           (RAD)  0.00000E+00  0.00000E+00
RACE ORBIT FRACTION             0.00000E+00  1.00000E+00
ROTATING LOAD SPEED      (RPM)  0.00000E+00  2.00000E+04

QUASI-STATIC CONSTRAINTS         0   1   0      TRANSLATIONAL CONSTRAINTS      1  1  1    1  1  1
CONSTRAINING LOAD FRACTION   0.00000E+00        ROTATIONAL CONSTRAINTS         1          1
```

		X-COMP	Y-COMP	Z-COMP
APPLIED LOAD VECTOR	(N)	5.00000E+03	0.00000E+00	2.00000E+03
RELATIVE DISPLACEMENT VECTOR	(M)	0.00000E+00	0.00000E+00	0.00000E+00
GRAVITY VECTOR	(M/S**2)	0.00000E+00	0.00000E+00	-9.81000E+00
CAGE MASS CENTER POSITION	(M)	0.00000E+00	0.00000E+00	-1.00000E-04
CAGE ANGULAR POSITION	(DEG)	0.00000E+00	0.00000E+00	0.00000E+00

```
SCALE FACTORS AND OUTPUT CONTROLS
---------------------------------


      ......SCALE FACTORS.......        ......STEP SIZE INFO......       NO OF STEPS    4000
      LENGTH   (M)  9.52500E-03     MINIMUM      5.00000E-03         DATA CONTROL     9    500
      LOAD     (N)  5.00000E+03     MAXIMUM      3.00000E-01         AUTO PLOTS       1     13      0
      TIME     (S)  2.31180E-04     INITIAL      5.00000E-02                          0      0      0
                                    ERROR LIMIT  1.00000E-04         INT METHOD       5
                                                                     TRACTION INT     1


OUTPUT FROM USER ACCESSIBLE ROUTINES ---
***************************************



STEP        TAU           TIME      OUTER RACE ROT  INNER RACE ROT
NO                         (S)          (DEG)           (DEG)
  0      0.000E+00     0.000E+00     0.000E+00       0.000E+00       Ball Bearing Test Case
=====     ==========    ==========   ==========      ==========      ===================================


1. ROLLING ELEMENT PARAMETERS
   --------------------------


RE ...ORBITAL ....CONTACT ANGLE.... ....CONTACT LOAD..... ...CONTACT STRESS.... ..MAJOR HALF WIDTH... ..MINOR HALF WIDTH...
NO   POSITION       (DEG)                   (N)                  (PA)                    (M)                   (M)
        (DEG) OUTER RACE INNER RACE OUTER RACE INNER RACE OUTER RACE INNER RACE OUTER RACE INNER RACE OUTER RACE INNER RACE

 1  0.000E+00  8.904E+00  2.756E+01  2.533E+03  8.470E+02  1.593E+09  1.431E+09  2.391E-03  1.290E-03  3.174E-04  2.192E-04
10  1.800E+02  4.704E+00  3.020E+01  2.160E+03  3.517E+02  1.510E+09  1.066E+09  2.268E-03  9.618E-04  3.011E-04  1.638E-04


RE ...ORBITAL ........ANGULAR VELOCITY........ ...RE ANG POSITION... ......SPIN/ROLL...... ....CONTACT LOSS..... ..TIME AVE
     VELOCITY AMPLITUDE   THETA      PHI      THETA      PHI                                     (N*M/S)         WEAR RATE
      (RPM)    (RPM)     (DEG)      (DEG)     (DEG)      (DEG) OUTER RACE INNER RACE OUTER RACE INNER RACE    (M**3/S)

 1  9.015E+03  7.546E+04 -7.845E+00  0.000E+00  7.845E+00  1.800E+02  8.184E-17  3.781E-01  8.154E+00  2.237E+01  1.801E-12
10  9.263E+03  7.758E+04 -4.143E+00  3.600E+02  4.143E+00  1.800E+02  3.250E-16  5.000E-01  4.271E+00  3.965E+00  9.937E-13


RE ....SLIP VELOCITY.... ......TRAC COEFF...... ....ISO LUB FILM..... ...THERMAL RED FAC... ......DRAG ..CHUR MOM ..NET LOSS
NO       (M/S)                                         (M)                                       (N)      (N*M)    (N*M/S)
   OUTER RACE INNER RACE OUTER RACE INNER RACE OUTER RACE INNER RACE OUTER RACE INNER RACE                        (DRAG+CHUR)

 1  1.649E+00  4.475E+00  2.241E-03  6.689E-03  1.293E-06  1.181E-06  2.884E-01  3.232E-01
10  1.520E+00  4.018E+00  1.817E-03  4.164E-03  1.332E-06  1.239E-06  2.863E-01  3.580E-01


RE .CONTACT DEFLECTION.. ....RACE FLEXING..... ..CONTACT TEMP RISE..
NO       (M)                   (M)                   (K)
   OUTER RACE INNER RACE OUTER RACE INNER RACE OUTER RACE INNER RACE
 1  1.621E-05  9.335E-06  0.000E+00  0.000E+00  5.635E+01  3.521E+02
10  1.458E-05  5.193E-06  0.000E+00  0.000E+00  3.177E+01  9.868E+01
```

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STEP NO	TAU	TIME (S)	OUTER RACE ROT (DEG)	INNER RACE ROT (DEG)	
0	0.000E+00	0.000E+00	0.000E+00	0.000E+00	Ball Bearing Test Case
=====	==========	==========	==========	==========	====================================

2. RACE AND CAGE PARAMETERS

RE NO C C	GEO INT (M)	......................RE/CAGE INTERACTION.......................				
		CONTACT FORCE (N)	CONTACT ANGLE 1 (DEG)	CONTACT ANGLE 2 (DEG)	CONTACT LOSS (N*M/S)	TIME AVE WEAR RATE (M**3/S)
1 0	4.171E-04	0.000E+00	2.700E+02	9.000E+01	0.000E+00	0.000E+00
2 0	3.979E-04	0.000E+00	3.360E+02	9.000E+01	0.000E+00	0.000E+00
3 0	3.725E-04	0.000E+00	3.491E+02	9.000E+01	0.000E+00	0.000E+00
4 0	3.531E-04	0.000E+00	3.547E+02	9.000E+01	0.000E+00	0.000E+00
5 0	3.426E-04	0.000E+00	3.585E+02	9.000E+01	0.000E+00	0.000E+00
6 0	3.426E-04	0.000E+00	1.723E+00	9.000E+01	0.000E+00	0.000E+00
7 0	3.530E-04	0.000E+00	5.364E+00	9.000E+01	0.000E+00	0.000E+00
8 0	3.726E-04	0.000E+00	1.082E+01	9.000E+01	0.000E+00	0.000E+00
9 0	3.980E-04	0.000E+00	2.362E+01	9.000E+01	0.000E+00	0.000E+00
10 0	4.174E-04	0.000E+00	9.000E+01	9.000E+01	0.000E+00	0.000E+00
11 0	3.980E-04	0.000E+00	1.564E+02	9.000E+01	0.000E+00	0.000E+00
12 0	3.726E-04	0.000E+00	1.692E+02	9.000E+01	0.000E+00	0.000E+00
13 0	3.530E-04	0.000E+00	1.746E+02	9.000E+01	0.000E+00	0.000E+00
14 0	3.426E-04	0.000E+00	1.783E+02	9.000E+01	0.000E+00	0.000E+00
15 0	3.426E-04	0.000E+00	1.815E+02	9.000E+01	0.000E+00	0.000E+00
16 0	3.531E-04	0.000E+00	1.853E+02	9.000E+01	0.000E+00	0.000E+00
17 0	3.725E-04	0.000E+00	1.909E+02	9.000E+01	0.000E+00	0.000E+00
18 0	3.979E-04	0.000E+00	2.040E+02	9.000E+01	0.000E+00	0.000E+00

LAND NO C C	.............RACE/CAGE FORCES.............				RACE/CAGE GEO INT (M)	RACE/CAGE SLIP VEL (M/S)	EFFECTIVE DIA PLAY (M)	CONTACT LOSS (N*M/S)	TIME AVE WEAR RATE (M**3/S)
	NORMAL (N)	TRACTION (N)	CON ANGLE (DEG)	ATT ANGLE (DEG)					
1 0	0.000E+00	0.000E+00	0.000E+00	0.000E+00	6.020E-04	0.000E+00	1.404E-03	0.000E+00	0.000E+00
2 0	0.000E+00	0.000E+00	0.000E+00	0.000E+00	6.020E-04	0.000E+00	1.404E-03	0.000E+00	0.000E+00

	......MASS CENTER POSITION.....			...ORBITAL		........ANGULAR VELOCITY........		....ANG POSITION.....		......HOOP	..TIME AVE
	AXIAL (M)	RADIAL (M)	ORBITAL (DEG)	VELOCITY (RPM)	AMPLITUDE (RPM)	THETA (DEG)	PHI (DEG)	THETA (DEG)	PHI (DEG)	STRESS (PA)	WEAR RATE (M**3/S)
CAGE	-1.142E-04	9.054E-05	1.800E+02	9.135E+03	9.135E+03	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
ORACE	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	-6.400E+06	1.116E-11
IRACE	-6.465E-05	9.463E-06	0.000E+00	2.000E+04	2.000E+04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.183E+08	1.343E-11

3. APPLIED PARAMETERS

		.........APPLIED FORCES.........		.......APPLIED MOMENTS.........				BASIC FATIGUE LIFE (HOURS)	4.904E+02
	(N)	(N)	(N)	(N*M)	(N*M)	(N*M)	MODIFIED FATIGUE LIFE (HOURS)	1.471E+03
	COMP-X	COMP-Y	COMP-Z	COMP-X	COMP-Y	COMP-Z	INTERNAL CLEARANCE (M)	1.525E-04
							OUTER RACE FIT (M)	1.000E-05
							INNER RACE FIT (M)	9.767E-07
CAGE	0.000E+00	0.000E+00	-6.244E+00	0.000E+00	0.000E+00	0.000E+00		
ORACE	5.003E+03	1.624E+01	1.559E+03	-6.866E+00	6.706E+01	3.563E-02	TOTAL POWER LOSS (N*M/S)	3.237E+02
IRACE	-5.000E+03	1.202E+00	-2.000E+03	-1.643E-01	-6.815E+01	-3.308E-02	CHURNING LOSS FRACTION	0.000E+00

4. TIME STEP SUMMARY

					....................TIME AVERAGE PARAMETERS....................				
STEP NO	TIME (S)	OUTER RACE ROTATION (DEG)	INNER RACE ROTATION (DEG)	FATIGUE LIFE (HOURS)	POWER LOSS (N*M/S)	RE ORBITAL VEL RATIO	CAGE OMEGA RATIO	CAGE WHIRL RATIO	CAGE WEAR RATE (M**3/S)
0	0.000E+00	0.000E+00	0.000E+00	1.471E+03	3.237E+02	4.567E-01	4.567E-01	4.567E-01	0.000E+00

Cylindrical Roller Bearing Test Case

A 30mm cylindrical roller bearing with ceramic rollers is used for the cylindrical roller bearing test case. The bearing is subjected to a fixed radial load of 250 N and it operates at a shaft speed of 70,000 rpm. Detailed bearing geometry, material properties and operating conditions, along the the solutions at step zero are presented below.

```
LISTING OF INPUT DATA RECORDS ---
*****************************

Rec 1              1     0     0     1    500     1     0  1000     5
Rec 2.1       5.0000E-02 1.0000E-04 5.0000E-01 1.0000E+03 1.0000E-04 0.0000E+00
Rec 3.1       Cyl Roller Bearing Test Case
Rec 3.2        2   2   0   0   8   0   0   1   1
Rec 3.3        1   1   0   0   0   0   1   0   0   0   0
Rec 3.4        0   0   0   0   1   2   1   9
Rec 4.1       3.0000E-02 5.5000E-02 1.0000E-02 6.5000E-02 1.2000E-02 1.2000E-02 0.0000E+00 2.0000E-05
Rec 4.2       2.9400E+02 2.9400E+02 2.9400E+02 2.9400E+02 2.9400E+02 2.9400E+02
Rec 5B        8.0000E-03 2.5000E-01 8.0000E-03 0.0000E+00 2.5000E-04 2.5000E-04 4.3000E-02 2.0000E-05
Rec 5B.1      1.0000E-02 0.0000E+00 1.0000E-02 0.0000E+00
Rec 5F        0.0000E+00 0.0000E+00 2.0000E+00 2.0000E+00 0.0000E+00 0.0000E+00 3.0000E-03 3.0000E-03 0.0000E+00 2.0000E-05
Rec 7.0        0   0   0   1   1   0   0   1   0
Rec 7.1       4.5000E-02 4.0000E-02 1.0000E-02 2.5000E-04 1.0000E-03 0.0000E+00 0.0000E+00
Rec 7.2.1     4.5000E-02 1.0000E-03 5.0000E-03 2.5000E-04
Rec 7.2.2     4.5000E-02 1.0000E-03 5.0000E-03 2.5000E-04
Rec 7.3       2.5000E-04 0.0000E+00 2.5000E-04 2.9400E+02 0.0000E+00 0.0000E+00 2.5000E-05 0.0000E+00 0.0000E+00 0.0000E+00
Rec 8.1       3.2000E+03 3.1000E+11 2.6000E-01 2.9000E-06 8.3700E+02 3.0500E+01 2.0000E-03 8.0000E+01 2.0000E-06
Rec 8.5       1.5000E+03 2.0000E+10 3.0000E-01 3.0000E-06 9.0000E+02 2.5000E+01 1.0000E-02 6.0000E+00 1.0000E-05
Rec 9.1.1     0.0000E+00 0.0000E+00 2.5000E+02 0.0000E+00 0.0000E+00 0.0000E+00
Rec 9.1.2     0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 7.0000E+04
Rec 10.1      0.0000E+00 1.0000E-01 0.0000E+00-1.5000E-01
Rec 10.2      5.0000E-02 0.0000E+00 0.0000E+00-5.0000E-02 5.0000E-07
Rec 10.5.1    5.0000E-02 0.0000E+00 0.0000E+00-5.0000E-02 5.0000E-07
Rec 10.5.2    5.0000E-02 0.0000E+00 0.0000E+00-5.0000E-02 5.0000E-07
Rec 11        0.0000E+00 0.0000E+00 9.8100E+00

INPUT FROM USER ACCESSIBLE ROUTINES ---
***********************************
```

```
         AAAAAAAAA   DDDDDDDDD    OOOOOOOOO   RRRRRRRRR    EEEEEEEEEEE
         AAAAAAAAAAA  DDDDDDDDDD   OOOOOOOOOOO  RRRRRRRRRR   EEEEEEEEEEE
         AA       AA  DD      DD  OO      OO  RR     RR   EE
         AA       AA  DD      DD  OO      OO  RR     RR   EE
         AA       AA  DD      DD  OO      OO  RRRRRRRRR   EEEEEE
         AA       AA  DD      DD  OO      OO  RRRRRRRRR   EEEEEE
         AAAAAAAAAAA  DD      DD  OO      OO  RR  RR      EE
         AAAAAAAAAAA  DD      DD  OO      OO  RR   RR     EE
         AA       AA  DDDDDDDDDD  OOOOOOOOOOO  RR    RR    EEEEEEEEEEE
         AA       AA  DDDDDDDDD    OOOOOOOOO   RR    RR    EEEEEEEEEEE

         ADVANCED      DYNAMICS     OF    ROLLING      ELEMENTS
         ========      ========     ==    =======      ========


              -A REAL TIME SIMULATION OF ROLLING BEARING PERFORMANCE-
                            (VERSION ADORE-3.5 )


                                  COPYRIGHT
                             PRADEEP K GUPTA INC
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```
*******************************************************************************************************
*                                                                                                     *
*    BEARING TYPE = CYLINDRICAL ROLLER         PROGRAM MODE = 1    SPEC CODE = Cyl Roller Bearing Test Case   *
*                                                                                                     *
*******************************************************************************************************
```

BEARING GEOMETRY

NO OF ROLLERS	8	PITCH DIA	(M) 4.30000E-02	OUTER FIT	(M) 0.00000E+00	SHAFT OD (M) 3.00000E-02
ROLLER DIA (M) 8.00000E-03		CROWN RAD	(M) 2.50000E-01	INNER FIT	(M) 2.00000E-05	SHAFT ID (M) 1.00000E-02
ROLLER LEN (M) 8.00000E-03		COR RAD I	(M) 2.50000E-04	DIA PLAY	(M) 2.00000E-05	BEARING OD (M) 5.50000E-02
CEN LAND (M) 0.00000E+00		COR RAD II	(M) 2.50000E-04			HOUSING OD (M) 6.50000E-02
OUTER LEN1 (M) 1.00000E-02		INNER LEN1	(M) 1.00000E-02	OUTER CRN	(M) 1.00000E+10	WIDTH I (M) 1.20000E-02
OUTER LEN2 (M) 1.00000E-02		INNER LEN2	(M) 0.00000E+00	INNER CRN	(M) 1.00000E+10	WIDTH II (M) 1.20000E-02

CAGE OD (M) 4.50000E-02	CAGE WIDTH (M) 1.00000E-02	LAND DIA (M) 4.50000E-02	LAND WIDTH (M) 1.00000E-03
CAGE ID (M) 4.00000E-02	POC CLS I (M) 2.50000E-04		4.50000E-02		1.00000E-03
OUTER CLS (M) 2.50000E-04	POC CLS II (M) 0.00000E+00	LAND CLS (M) 2.50000E-04	LAND POS (M) 5.00000E-03
INNER CLS (M) 1.00000E-03	POCKET SHAPE 0		2.50000E-04		5.00000E-03
GUIDE LAND TYPE 1 1			

	FLANGE CLS (M)	FLANGE HT I (M)	FLANGE HT II (M)	LAYBACK I (DEG)	LAYBACK II (DEG)
INNER RACE	2.00000E-05	3.00000E-03	3.00000E-03	2.00000E+00	2.00000E+00

MATERIAL PROPERTIES

		ROLLING ELEMENT	OUTER RACE	INNER RACE	CAGE	SHAFT	HOUSING
DENSITY	(KGM/M**3)	3.20000E+03	7.75037E+03	7.75037E+03	1.50000E+03	7.75037E+03	7.75037E+03
ELASTIC MODULUS	(PA)	3.10000E+11	1.99948E+11	1.99948E+11	2.00000E+11	1.99948E+11	1.99948E+11
POISSON-S RATIO		2.60000E-01	2.50000E-01	2.50000E-01	3.00000E-01	2.50000E-01	2.50000E-01
COEFF OF THERMAL EXP	(1/K)	2.90000E-06	1.17000E-05	1.17000E-05	3.00000E-06	1.17000E-05	1.17000E-05
HEAT CAPACITY	(N*M/KGM/K)	8.37000E+02	4.70000E+02	4.70000E+02	9.00000E+02		
THERMAL CONDUCTIVITY	(N/S/K)	3.05000E+01	4.30000E+01	4.30000E+01	2.50000E+01		
ELASTIC STRAIN LIMIT		2.00000E-03	2.00000E-03	2.00000E-03	1.00000E-02		
HARDNESS	(RC)	8.00000E+01	6.10000E+01	6.10000E+01	6.00000E+00		
WEAR COEFFICIENT		2.00000E-06	5.00000E-06	5.00000E-06	1.00000E-05		

INERTIAL PARAMETERS

	.......MASS (KGM)	..........MOMENT OF INERTIA.......... (KGM*M**2)			.........MASS TO GEO CENTER......... (M)		
		X-COMP	Y-COMP	Z-COMP	X-COMP	Y-COMP	Z-COMP
RE	1.28002E-03	1.02401E-08	1.19468E-08	1.19468E-08	0.00000E+00	0.00000E+00	0.00000E+00
CAGE	3.02691E-03	1.37157E-06	7.11009E-07	7.11009E-07	0.00000E+00	0.00000E+00	0.00000E+00

```
.........PRINCIPAL TO GEO FRAME........
                        (DEG)
           X-COMP      Y-COMP      Z-COMP


   RE  0.00000E+00  0.00000E+00  0.00000E+00
 CAGE  0.00000E+00  0.00000E+00  0.00000E+00
```

LUBRICATION PARAMETERS

	CRITICAL FILM (M)	TRAC COEFF AT ZERO SLIP	MAXIMUM TRAC COEFF	TRAC COEFF AT INF SLIP	SLIP AT MAX TRACTION (M/S)	COEFFICIENT A	COEFFICIENT B (S/M)	COEFFICIENT C (S/M)	COEFFICIENT D
RE/RACE	0.00000E+00					0.00000E+00	1.00000E-01	0.00000E+00	-1.50000E-01
RE/CAGE	5.00000E-07					5.00000E-02	0.00000E+00	0.00000E+00	-5.00000E-02
CAGE/RACE	5.00000E-07					5.00000E-02	0.00000E+00	0.00000E+00	-5.00000E-02
RE/FLANGE	5.00000E-07					5.00000E-02	0.00000E+00	0.00000E+00	-5.00000E-02

LUBRICANT CODE..... 0 HYPOTHETICAL MODEL

FATIGUE PARAMETERS

	................FATIGUE CONSTANTS................		.....LOAD EXPONENTS.....		....LIFE MULTIPLIERS....		WEIBULL
	POINT CONTACT (N/M**1.80)	LINE CONTACT (N/M**(50/27))	POINT CONT	LINE CONT	MAT MATRIX	SUR DEFECTS	DISPERSION EXPONENT
OUTER RACE	1.87431E+07	1.66550E+08	3.00000E+00	4.00000E+00	1.00000E+00	1.00000E+00	1.11111E+00
INNER RACE	1.87431E+07	1.66550E+08	3.00000E+00	4.00000E+00	1.00000E+00	1.00000E+00	1.11111E+00

	COMPOSITE RMS ASPERITY HEIGHT (M)	COMPOSITE RMS ASPERITY SLOPE (RAD)	EFFECTIVE HARDNESS (RC)	PLASTIC SHEAR STRESS LIMIT (PA)	ASPERITY TRACTION COEFFICIENT	EMPERICAL SURFACE HAZARD CONSTANT	
OUTER RACE	1.00000E-07	2.00000E-02	6.10000E+01	2.47997E+08	1.20000E-01	3.70508E+00	
INNER RACE	1.00000E-07	2.00000E-02	6.10000E+01	2.47997E+08	1.20000E-01	3.70508E+00	

BEARING WEIBULL SLOPE 1.11111E+00
LIFE MODIFICATION CODE 0

INITIAL OPERATING CONDITIONS   Cyl Roller Bearing Test Case

			OUTER RACE	INNER RACE
ROOM TEMPERATURE	(K)	2.94000E+02		
HOUSING TEMPERATURE	(K)	2.94000E+02		
SHAFT TEMPERATURE	(K)	2.94000E+02		
ROLLING ELEMENT TEMPERATURE	(K)	2.94000E+02		
CAGE TEMPERATURE	(K)	2.94000E+02		

```
                                              OUTER RACE   INNER RACE

ANGULAR VELOCITY       (RPM)  0.00000E+00  7.00000E+04
TEMPERATURE            (K)    2.94000E+02  2.94000E+02
MISALIGNMENT-Y         (RAD)  0.00000E+00  0.00000E+00
MISALIGNMENT-Z         (RAD)  0.00000E+00  0.00000E+00

QUASI-STATIC CONSTRAINTS          1   1   0
CONSTRAINING LOAD FRACTION    0.00000E+00

TRANSLATIONAL CONSTRAINTS    1   1   1    1   1   1
ROTATIONAL CONSTRAINTS       1            1
```

```
                                    X-COMP        Y-COMP        Z-COMP

APPLIED LOAD VECTOR          (N)    0.00000E+00  0.00000E+00  2.50000E+02
RELATIVE DISPLACEMENT VECTOR (M)    0.00000E+00  0.00000E+00  0.00000E+00
GRAVITY VECTOR          (M/S**2)    0.00000E+00  0.00000E+00  9.81000E+00
CAGE MASS CENTER POSITION    (M)    0.00000E+00  0.00000E+00  2.50000E-05
CAGE ANGULAR POSITION      (DEG)    0.00000E+00  0.00000E+00  0.00000E+00
```

SCALE FACTORS AND OUTPUT CONTROLS

```
    ......SCALE FACTORS.......        ......STEP SIZE INFO......      NO OF STEPS    1000
    LENGTH  (M) 4.00000E-03           MINIMUM     1.00000E-04         DATA CONTROL      1   500
    LOAD    (N) 2.50000E+02           MAXIMUM     5.00000E-01         AUTO PLOTS        1     9     0
    TIME    (S) 1.43109E-04           INITIAL     5.00000E-02                           0     0     0
                                      ERROR LIMIT 1.00000E-04         INT METHOD        5
                                                                      ROLLER MESH      12
```

OUTPUT FROM USER ACCESSIBLE ROUTINES ---
****

STEP NO	TAU	TIME (S)	OUTER RACE ROT (DEG)	INNER RACE ROT (DEG)	
0	0.000E+00	0.000E+00	0.000E+00	0.000E+00	Cyl Roller Bearing Test Case
=====	==========	==========	==========	==========	======================================

1. ROLLING ELEMENT PARAMETERS

RE NO	...ORBITAL POSITION (DEG)	....CONTACT ANGLE.... (DEG)		....CONTACT LOAD..... (N)		...CONTACT STRESS.... (PA)		..MAJOR HALF WIDTH... (M)		..MINOR HALF WIDTH... (M)	
		OUTER RACE	INNER RACE	OUTER RACE	INNER RACE	OUTER RACE	INNER RACE	OUTER RACE	INNER RACE	OUTER RACE	INNER RACE
1	0.000E+00	0.000E+00	0.000E+00	3.987E+02	1.537E+02	1.428E+09	1.238E+09	1.289E-03	9.611E-04	1.034E-04	6.169E-05
2	4.500E+01	0.000E+00	0.000E+00	3.131E+02	6.810E+01	1.317E+09	9.436E+08	1.189E-03	7.327E-04	9.544E-05	4.703E-05
3	9.000E+01	0.000E+00	0.000E+00	2.450E+02	0.000E+00	1.214E+09	0.000E+00	1.096E-03	0.000E+00	8.794E-05	0.000E+00
4	1.350E+02	0.000E+00	0.000E+00	2.450E+02	0.000E+00	1.214E+09	0.000E+00	1.096E-03	0.000E+00	8.794E-05	0.000E+00
5	1.800E+02	0.000E+00	0.000E+00	2.450E+02	0.000E+00	1.214E+09	0.000E+00	1.096E-03	0.000E+00	8.794E-05	0.000E+00
6	2.250E+02	0.000E+00	0.000E+00	2.450E+02	0.000E+00	1.214E+09	0.000E+00	1.096E-03	0.000E+00	8.794E-05	0.000E+00
7	2.700E+02	0.000E+00	0.000E+00	2.450E+02	0.000E+00	1.214E+09	0.000E+00	1.096E-03	0.000E+00	8.794E-05	0.000E+00
8	3.150E+02	0.000E+00	0.000E+00	3.131E+02	6.810E+01	1.317E+09	9.436E+08	1.189E-03	7.327E-04	9.544E-05	4.703E-05

RE	...ORBITAL VELOCITY (RPM)	........ANGULAR VELOCITY........			...RE ANG POSITION...		......SPIN/ROLL......		....CONTACT LOSS..... (N*M/S)		..TIME AVE WEAR RATE (M**3/S)
		AMPLITUDE (RPM)	THETA (DEG)	PHI (DEG)	THETA (DEG)	PHI (DEG)	OUTER RACE	INNER RACE	OUTER RACE	INNER RACE	
1	2.849E+04	1.817E+05	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.428E-03	6.139E-04	7.110E-16
2	2.849E+04	1.817E+05	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.381E-03	1.682E-03	5.899E-16
3	2.849E+04	1.817E+05	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	7.794E-04	0.000E+00	2.407E-16
4	2.849E+04	1.817E+05	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	7.794E-04	0.000E+00	2.407E-16
5	2.849E+04	1.817E+05	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	7.794E-04	0.000E+00	2.407E-16
6	2.849E+04	1.817E+05	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	7.794E-04	0.000E+00	2.407E-16
7	2.849E+04	1.817E+05	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	7.794E-04	0.000E+00	2.407E-16
8	2.849E+04	1.817E+05	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.381E-03	1.682E-03	5.899E-16

RE NO	....SLIP VELOCITY.... (M/S)		.....TRAC COEFF......		....ISO LUB FILM..... (M)		...THERMAL RED FAC...		......DRAG (N)	..CHUR MOM (N*M)	..NET LOSS (N*M/S) (DRAG+CHUR)
	OUTER RACE	INNER RACE	OUTER RACE	INNER RACE	OUTER RACE	INNER RACE	OUTER RACE	INNER RACE			
1	2.308E-02	1.869E-02	2.308E-03	1.869E-03							
2	1.965E-02	3.339E-02	1.965E-03	3.339E-03							
3	1.668E-02	0.000E+00	1.668E-03	0.000E+00							
4	1.668E-02	0.000E+00	1.668E-03	0.000E+00							
5	1.668E-02	0.000E+00	1.668E-03	0.000E+00							
6	1.668E-02	0.000E+00	1.668E-03	0.000E+00							
7	1.668E-02	0.000E+00	1.668E-03	0.000E+00							
8	1.965E-02	3.339E-02	1.965E-03	3.339E-03							

RE NO	.CONTACT DEFLECTION.. (M)		....RACE FLEXING..... (M)		..CONTACT TEMP RISE.. (K)	
	OUTER RACE	INNER RACE	OUTER RACE	INNER RACE	OUTER RACE	INNER RACE
1	4.451E-06	2.432E-06	0.000E+00	0.000E+00	6.790E-02	2.982E-02
2	3.789E-06	1.413E-06	0.000E+00	0.000E+00	4.360E-02	1.137E-01
3	3.217E-06	-2.079E-06	0.000E+00	0.000E+00	2.781E-02	0.000E+00
4	3.217E-06	-6.150E-06	0.000E+00	0.000E+00	2.781E-02	0.000E+00
5	3.217E-06	-7.839E-06	0.000E+00	0.000E+00	2.781E-02	0.000E+00
6	3.217E-06	-6.150E-06	0.000E+00	0.000E+00	2.781E-02	0.000E+00
7	3.217E-06	-2.079E-06	0.000E+00	0.000E+00	2.781E-02	0.000E+00
8	3.789E-06	1.413E-06	0.000E+00	0.000E+00	4.360E-02	1.137E-01

```
STEP        TAU          TIME      OUTER RACE ROT  INNER RACE ROT
NO                       (S)          (DEG)          (DEG)
  0       0.000E+00    0.000E+00    0.000E+00      0.000E+00      Cyl Roller Bearing Test Case
=====    ==========   ==========   ==========     ==========      ====================================
```

1B. RACE FLANGE INTERACTION

```
RE ....................................ROLLER/INNER RACE FLANGE INTERACTION......................................
NO     GEOM INTERACTION     CONTACT LOAD      MAJOR HALF WIDTH    MINOR HALF WIDTH     CONTACT LOSS      CONTACT
           (M)                  (N)                (M)                 (M)               (N*M/S)          CODE
     FLANGE I  FLANGE II   FLANGE I  FLANGE II  FLANGE I  FLANGE II  FLANGE I  FLANGE II  FLANGE I  FLANGE II  I II

 1  9.774E-06  9.774E-06  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0  0
 2  9.809E-06  9.809E-06  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0  0
 3  9.932E-06  9.932E-06  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0  0
 4  1.007E-05  1.007E-05  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0  0
 5  1.013E-05  1.013E-05  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0  0
 6  1.007E-05  1.007E-05  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0  0
 7  9.932E-06  9.932E-06  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0  0
 8  9.809E-06  9.809E-06  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0  0
```

1C. ROLLER END AND RACE FLANGE WEAR DISTRIBUTION

```
RE  TIME AVE WEAR RATE..     RE  TIME AVE WEAR RATE..     RE  TIME AVE WEAR RATE..     RE  TIME AVE WEAR RATE..
NO       (M**3/S)            NO       (M**3/S)            NO       (M**3/S)            NO       (M**3/S)
      END I     END II              END I     END II             END I     END II             END I     END II

 1  0.000E+00  0.000E+00      2  0.000E+00  0.000E+00      3  0.000E+00  0.000E+00      4  0.000E+00  0.000E+00
 5  0.000E+00  0.000E+00      6  0.000E+00  0.000E+00      7  0.000E+00  0.000E+00      8  0.000E+00  0.000E+00


      ......TIME AVE RACE FLANGE WEAR RATES......
                   (M**3/S)
       OUTER I    OUTER II   INNER I    INNER II
      0.000E+00  0.000E+00  0.000E+00  0.000E+00
```

```
STEP        TAU          TIME      OUTER RACE ROT  INNER RACE ROT
NO                       (S)          (DEG)          (DEG)
  0       0.000E+00    0.000E+00    0.000E+00      0.000E+00      Cyl Roller Bearing Test Case
=====    ==========   ==========   ==========     ==========      ====================================
```

2. RACE AND CAGE PARAMETERS

```
      RE .................RE/CAGE INTERACTION..................
      NO C   GEO INT    CONTACT    CONTACT    CONTACT    CONTACT    TIME AVE
         C              FORCE      POS 1      POS 2      LOSS       WEAR RATE
               (M)      (N)        (M)        (M)        (N*M/S)    (M**3/S)

      1 0  1.344E-04  0.000E+00  6.371E-11   2.345E-04  0.000E+00  0.000E+00
        0  1.344E-04  0.000E+00  6.371E-11  -2.345E-04  0.000E+00  0.000E+00
      2 0  1.521E-04  0.000E+00  6.280E-11   2.411E-04  0.000E+00  0.000E+00
        0  1.167E-04  0.000E+00  6.490E-11  -2.411E-04  0.000E+00  0.000E+00
      3 0  1.594E-04  0.000E+00  6.248E-11   2.582E-04  0.000E+00  0.000E+00
        0  1.094E-04  0.000E+00  6.550E-11  -2.582E-04  0.000E+00  0.000E+00
      4 0  1.521E-04  0.000E+00  6.280E-11   2.759E-04  0.000E+00  0.000E+00
        0  1.167E-04  0.000E+00  6.490E-11  -2.759E-04  0.000E+00  0.000E+00
      5 0  1.344E-04  0.000E+00  6.371E-11   2.832E-04  0.000E+00  0.000E+00
        0  1.344E-04  0.000E+00  6.371E-11  -2.832E-04  0.000E+00  0.000E+00
      6 0  1.167E-04  0.000E+00  6.490E-11   2.759E-04  0.000E+00  0.000E+00
        0  1.521E-04  0.000E+00  6.280E-11  -2.759E-04  0.000E+00  0.000E+00
      7 0  1.094E-04  0.000E+00  6.550E-11   2.582E-04  0.000E+00  0.000E+00
        0  1.594E-04  0.000E+00  6.248E-11  -2.582E-04  0.000E+00  0.000E+00
      8 0  1.167E-04  0.000E+00  6.490E-11   2.411E-04  0.000E+00  0.000E+00
        0  1.521E-04  0.000E+00  6.280E-11  -2.411E-04  0.000E+00  0.000E+00
```

LAND C NO C	.........RACE/CAGE FORCES.........				RACE/CAGE GEO INT (M)	RACE/CAGE SLIP VEL (M/S)	EFFECTIVE DIA PLAY (M)	CONTACT LOSS (N*M/S)	TIME AVE WEAR RATE (M**3/S)
	NORMAL (N)	TRACTION (N)	CON ANGLE (DEG)	ATT ANGLE (DEG)					
1 0	0.000E+00	0.000E+00	0.000E+00	-1.800E+02	1.000E-04	0.000E+00	2.500E-04	0.000E+00	0.000E+00
2 0	0.000E+00	0.000E+00	0.000E+00	-1.800E+02	1.000E-04	0.000E+00	2.500E-04	0.000E+00	0.000E+00

	......MASS CENTER POSITION.....			...ORBITAL		.......ANGULAR VELOCITY........		....ANG POSITION.....		......HOOP STRESS (PA)	..TIME AVE WEAR RATE (M**3/S)
	AXIAL (M)	RADIAL (M)	ORBITAL (DEG)	VELOCITY (RPM)	AMPLITUDE (RPM)	THETA (DEG)	PHI (DEG)	THETA (DEG)	PHI (DEG)		
CAGE	0.000E+00	2.500E-05	0.000E+00	2.849E+04	2.849E+04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
ORACE	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	8.097E-15
IRACE	0.000E+00	5.752E-06	0.000E+00	0.000E+00	7.000E+04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.532E+08	2.048E-15

STEP NO	TAU	TIME (S)	OUTER RACE ROT (DEG)	INNER RACE ROT (DEG)	
0	0.000E+00	0.000E+00	0.000E+00	0.000E+00	Cyl Roller Bearing Test Case
=====	==========	==========	==========	==========	==================================

3. APPLIED PARAMETERS

	.........APPLIED FORCES.........			........APPLIED MOMENTS........		
	(N) COMP-X	(N) COMP-Y	(N) COMP-Z	(N*M) COMP-X	(N*M) COMP-Y	(N*M) COMP-Z
CAGE	0.000E+00	0.000E+00	2.969E-02	0.000E+00	0.000E+00	0.000E+00
ORACE	-1.074E-31	-1.855E-01	2.500E+02	2.471E-02	-8.611E-19	6.699E-21
IRACE	-6.324E-18	9.052E-02	-2.500E+02	-7.647E-03	2.053E-18	2.525E-21

BASIC FATIGUE LIFE	(HOURS)	4.405E+01
MODIFIED FATIGUE LIFE	(HOURS)	4.405E+01
INTERNAL CLEARANCE	(M)	-2.261E-06
OUTER RACE FIT	(M)	0.000E+00
INNER RACE FIT	(M)	5.730E-06
TOTAL POWER LOSS	(N*M/S)	1.307E-02
CHURNING LOSS FRACTION		0.000E+00

4. TIME STEP SUMMARY

					....................TIME AVERAGE PARAMETERS....................				
STEP NO	TIME (S)	OUTER RACE ROTATION (DEG)	INNER RACE ROTATION (DEG)	FATIGUE LIFE (HOURS)	POWER LOSS (N*M/S)	RE ORBITAL VEL RATIO	CAGE OMEGA RATIO	CAGE WHIRL RATIO	CAGE WEAR RATE (M**3/S)
0	0.000E+00	0.000E+00	0.000E+00	4.405E+01	1.307E-02	4.070E-01	4.070E-01	4.070E-01	0.000E+00

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Tapered Roller Bearing Test Case

A hypothetical geometry is assumed for the test tapered roller bearing. The bearing operates with a thrust of 5,000 N and a fixed radial load of 500 N. The shaft speed is 2,500 rpm. The ouput below contains all the bearing geometry, material properties, operating conditions and the initial conditions which represent the solutions at step zero.

```
     LISTING OF INPUT DATA RECORDS ---
     *****************************

Rec 1            0      0      0    1  1000    4    0  4000     5
Rec 2.1      5.0000E-04 1.0000E-04 3.0000E-01 1.0000E+03 5.0000E-04 0.0000E+00
Rec 3.1      Test tapered bearing
Rec 3.2       2   4   0   0 22   0   0   1   0
Rec 3.3       0   1   0   0   1   0   0   0   0   0   2
Rec 3.4       0   0   0   0   1   2   1 23
Rec 4.1      1.5000E-01 2.2000E-01 1.0100E-01 2.5000E-01 3.8000E-02 4.6000E-02 0.0000E+00 0.0000E+00
Rec 4.2      3.0000E+02 3.0000E+02 3.0000E+02 3.0000E+02 3.0000E+02 3.0000E+02
Rec 5D       1.6000E-02 1.0000E+00 3.4000E-02 1.0000E-02 1.6000E-01 1.0000E+10 0.0000E+00 0.0000E+00 1.3000E+01 1.1000E+01
Rec 5D.1     3.8000E-02 0.0000E+00 3.8000E-02 0.0000E+00
Rec 5F       0.0000E+00 0.0000E+00-7.5000E-01 0.0000E+00 0.0000E+00 0.0000E+00 9.0000E-03 0.0000E+00 0.0000E+00 0.0000E+00
Rec 7.0       0   0   0   0   2   0   0   1   0
Rec 7.1      1.9500E-01 1.7500E-01 4.2000E-02 0.0000E+00 0.0000E+00 0.0000E+00 1.2000E+01
Rec 7.2.2    1.6500E-01 3.0000E-03 2.1000E-02 6.0000E-04
Rec 7.3      6.0000E-04 0.0000E+00 6.0000E-04 3.0000E+02 0.0000E+00 0.0000E+00-1.0000E-04 0.0000E+00 0.0000E+00 0.0000E+00
Rec 8.5      1.5000E+03 2.0000E+10 3.0000E-01 3.0000E-06 9.0000E+02 2.5000E+01 1.0000E-02 6.0000E+00 1.0000E-05
Rec 9.1.1    5.0000E+03 0.0000E+00 5.0000E+02 0.0000E+00 0.0000E+00 0.0000E+00
Rec 9.1.2    0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 2.5000E+03
Rec 10.1     0.0000E+00 1.0000E-02 7.0000E-03 2.5000E+01
Rec 10.2     0.0000E+00 1.0000E-02 7.0000E-03 2.5000E+01 0.0000E+00
Rec 10.3     1.0000E-07 1.0000E+01
Rec 10.5.1   1.0000E-02 0.0000E+00 0.0000E+00-1.0000E-02 1.0000E-07
Rec 10.5.2   1.0000E-02 0.0000E+00 0.0000E+00-1.0000E-02 1.0000E-07
Rec 11       0.0000E+00 0.0000E+00-9.8100E+00


     INPUT FROM USER ACCESSIBLE ROUTINES ---
     ***********************************
```

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```
AAAAAAAAA   DDDDDDDDD    OOOOOOOO   RRRRRRRRR   EEEEEEEEEE
AAAAAAAAAAA  DDDDDDDDDD  OOOOOOOOOOO  RRRRRRRRRR  EEEEEEEEEEE
AA      AA   DD    DD   OO      OO   RR    RR  EE
AA      AA   DD    DD   OO      OO   RR    RR  EE
AA      AA   DD    DD   OO      OO   RRRRRRRRR  EEEEEE
AA      AA   DD    DD   OO      OO   RRRRRRRRR  EEEEEE
AAAAAAAAAAA  DD    DD   OO      OO   RR RR     EE
AAAAAAAAAAA  DD    DD   OO      OO   RR RR     EE
AA      AA  DDDDDDDDDD  OOOOOOOOOOO  RR    RR  EEEEEEEEEEE
AA      AA  DDDDDDDDD    OOOOOOOO   RR    RR  EEEEEEEEEEE

ADVANCED      DYNAMICS     OF    ROLLING      ELEMENTS
========      ========     ==    =======      ========
```

-A REAL TIME SIMULATION OF ROLLING BEARING PERFORMANCE-
(VERSION ADORE-3.5)

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PRADEEP K GUPTA INC

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*******************************************************************************************************************
*                                                                                                                 *
*    BEARING TYPE = TAPERED ROLLER            PROGRAM MODE = 0     SPEC CODE = Test tapered bearing              *
*                                                                                                                 *
*******************************************************************************************************************
```

BEARING GEOMETRY

NO OF ROLLERS 22	OUT CONE (DEG) 1.30000E+01	COR RAD I (M) 0.00000E+00	SHAFT OD (M) 1.50000E-01
ROLLER DIA (M) 1.60000E-02	IN CONE (DEG) 1.10000E+01	COR RAD II (M) 0.00000E+00	SHAFT ID (M) 1.01000E-01
ROLLER LEN (M) 3.40000E-02	END RAD I (M) 1.60000E-01	OUTER FIT (M) 0.00000E+00	BEARING OD (M) 2.20000E-01
CEN LAND (M) 1.00000E-02	END RAD II (M) 1.00000E+10	INNER FIT (M) 0.00000E+00	HOUSING OD (M) 2.50000E-01
CROWN RAD (M) 1.00000E+00	OUTER LEN1 (M) 3.80000E-02	INNER LEN1 (M) 3.80000E-02	WIDTH I (M) 3.80000E-02
OUTER CRN (M) 1.00000E+10	OUTER LEN2 (M) 0.00000E+00	INNER LEN2 (M) 0.00000E+00	WIDTH II (M) 4.60000E-02
INNER CRN (M) 1.00000E+10			

CAGE OD (M) 1.95000E-01	CAGE WIDTH (M) 4.20000E-02	LAND DIA (M) 0.00000E+00	LAND WIDTH (M) 0.00000E+00
CAGE ID (M) 1.75000E-01	POC CLS I (M) 6.00000E-04		1.65000E-01		3.00000E-03
OUTER CLS (M) 0.00000E+00	POC CLS II (M) 0.00000E+00	LAND CLS (M) 0.00000E+00	LAND POS (M) 0.00000E+00
INNER CLS (M) 0.00000E+00	POCKET SHAPE 0		6.00000E-04		2.10000E-02
GUIDE LAND TYPE 0 2			
CAGE CONE (DEG) 1.20000E+01			

	FLANGE CLS (M)	FLANGE HT I (M)	FLANGE HT II (M)	LAYBACK I (DEG)	LAYBACK II (DEG)
INNER RACE	0.00000E+00	9.00000E-03		-7.50000E-01	

MATERIAL PROPERTIES

		ROLLING ELEMENT	OUTER RACE	INNER RACE	CAGE	SHAFT	HOUSING
DENSITY	(KGM/M**3)	7.75037E+03	7.75037E+03	7.75037E+03	1.50000E+03	7.75037E+03	7.75037E+03
ELASTIC MODULUS	(PA)	1.99948E+11	1.99948E+11	1.99948E+11	2.00000E+10	1.99948E+11	1.99948E+11
POISSON-S RATIO		2.50000E-01	2.50000E-01	2.50000E-01	3.00000E-01	2.50000E-01	2.50000E-01
COEFF OF THERMAL EXP	(1/K)	1.17000E-05	1.17000E-05	1.17000E-05	3.00000E-06	1.17000E-05	1.17000E-05
HEAT CAPACITY	(N*M/KGM/K)	4.70000E+02	4.70000E+02	4.70000E+02	9.00000E+02		
THERMAL CONDUCTIVITY	(N/S/K)	4.30000E+01	4.30000E+01	4.30000E+01	2.50000E+01		
ELASTIC STRAIN LIMIT		2.00000E-03	2.00000E-03	2.00000E-03	1.00000E-02		
HARDNESS	(RC)	6.10000E+01	6.10000E+01	6.10000E+01	6.00000E+00		
WEAR COEFFICIENT		5.00000E-06	5.00000E-06	5.00000E-06	1.00000E-05		

INERTIAL PARAMETERS

	.......MASS (KGM)	..........MOMENT OF INERTIA.......... (KGM*M**2)			..........MASS TO GEO CENTER.......... (M)		
		X-COMP	Y-COMP	Z-COMP	X-COMP	Y-COMP	Z-COMP
RE	4.91491E-02	1.46187E-06	5.45815E-06	5.45815E-06	0.00000E+00	0.00000E+00	0.00000E+00
CAGE	3.01370E-01	2.58613E-03	1.33737E-03	1.33737E-03	0.00000E+00	0.00000E+00	0.00000E+00

```
         .........PRINCIPAL TO GEO FRAME........
                          (DEG)
                 X-COMP      Y-COMP       Z-COMP


      RE  0.00000E+00  0.00000E+00  0.00000E+00
    CAGE  0.00000E+00  0.00000E+00  0.00000E+00
```

LUBRICATION PARAMETERS

	CRITICAL FILM (M)	TRAC COEFF AT ZERO SLIP	MAXIMUM TRAC COEFF	TRAC COEFF AT INF SLIP	SLIP AT MAX TRACTION (M/S)	COEFFICIENT A	COEFFICIENT B (S/M)	COEFFICIENT C (S/M)	COEFFICIENT D
RE/RACE	1.00000E-07	0.00000E+00	1.00000E-02	7.00000E-03	2.50000E+01				
RE/CAGE	1.00000E-07					1.00000E-02	0.00000E+00	0.00000E+00	-1.00000E-02
CAGE/RACE	1.00000E-07					1.00000E-02	0.00000E+00	0.00000E+00	-1.00000E-02
RE/FLANGE	0.00000E+00	0.00000E+00	1.00000E-02	7.00000E-03	2.50000E+01				

LUBRICANT CODE..... 1 MOBIL DTE

	REF TEMP (K)	VISCOSITY (PA*S)	PR-VIS COEFFICIENT (1/PA)	TEMP-VIS COEFF TYPE 1 (1/K)	TEMP-VIS COEFF TYPE 2 (K)	THERMAL CONDUCTIVITY (N/S/K)	STARVATION PARAMETER	REF ROLLING VELOCITY (M/S)
LUB FILM	3.00000E+02	1.16809E-01	1.90000E-08		4.10430E+03	9.60820E-02	1.00000E+01	
TRACTION	3.00000E+02	3.79887E-01	7.25160E-09	2.62064E-02				2.54000E+01

FATIGUE PARAMETERS

	........FATIGUE CONSTANTS........		.....LOAD EXPONENTS.....		....LIFE MULTIPLIERS....		WEIBULL
	POINT CONTACT (N/M**1.80)	LINE CONTACT (N/M**(50/27))	POINT CONT	LINE CONT	MAT MATRIX	SUR DEFECTS	DISPERSION EXPONENT
OUTER RACE	1.87431E+07	1.66550E+08	3.00000E+00	4.00000E+00	1.00000E+00	1.00000E+00	1.11111E+00
INNER RACE	1.87431E+07	1.66550E+08	3.00000E+00	4.00000E+00	1.00000E+00	1.00000E+00	1.11111E+00

	COMPOSITE RMS ASPERITY HEIGHT (M)	COMPOSITE RMS ASPERITY SLOPE (RAD)	EFFECTIVE HARDNESS (RC)	PLASTIC SHEAR STRESS LIMIT (PA)	ASPERITY TRACTION COEFFICIENT	EMPERICAL SURFACE HAZARD CONSTANT	
OUTER RACE	1.00000E-07	2.00000E-02	6.10000E+01	2.47997E+08	1.20000E-01	3.70508E+00	
INNER RACE	1.00000E-07	2.00000E-02	6.10000E+01	2.47997E+08	1.20000E-01	3.70508E+00	

BEARING WEIBULL SLOPE 1.11111E+00
LIFE MODIFICATION CODE 2

INITIAL OPERATING CONDITIONS   Test tapered bearing

				OUTER RACE	INNER RACE
ROOM TEMPERATURE	(K)	3.00000E+02	ANGULAR VELOCITY (RPM)	0.00000E+00	2.50000E+03
HOUSING TEMPERATURE	(K)	3.00000E+02	TEMPERATURE (K)	3.00000E+02	3.00000E+02
SHAFT TEMPERATURE	(K)	3.00000E+02	MISALIGNMENT-Y (RAD)	0.00000E+00	0.00000E+00
ROLLING ELEMENT TEMPERATURE	(K)	3.00000E+02	MISALIGNMENT-Z (RAD)	0.00000E+00	0.00000E+00
CAGE TEMPERATURE	(K)	3.00000E+02			

```
QUASI-STATIC CONSTRAINTS            0   1   0      TRANSLATIONAL CONSTRAINTS      1  1  1    1  1  1
CONSTRAINING LOAD FRACTION       0.00000E+00       ROTATIONAL CONSTRAINTS         1          1
```

		X-COMP	Y-COMP	Z-COMP
APPLIED LOAD VECTOR	(N)	5.00000E+03	0.00000E+00	5.00000E+02
RELATIVE DISPLACEMENT VECTOR	(M)	0.00000E+00	0.00000E+00	0.00000E+00
GRAVITY VECTOR	(M/S**2)	0.00000E+00	0.00000E+00	-9.81000E+00
CAGE MASS CENTER POSITION	(M)	0.00000E+00	0.00000E+00	-1.00000E-04
CAGE ANGULAR POSITION	(DEG)	0.00000E+00	0.00000E+00	0.00000E+00

SCALE FACTORS AND OUTPUT CONTROLS

```
        ......SCALE FACTORS.......        ......STEP SIZE INFO......      NO OF STEPS    4000
        LENGTH    (M)  8.00000E-03     MINIMUM     1.00000E-04      DATA CONTROL    1  1000
        LOAD      (N)  5.00000E+03     MAXIMUM     3.00000E-01      AUTO PLOTS      1    23      0
        TIME      (S)  2.80426E-04     INITIAL     5.00000E-04                      0     0      0
                                       ERROR LIMIT 5.00000E-04      INT METHOD      5
                                                                    ROLLER MESH    12
```

OUTPUT FROM USER ACCESSIBLE ROUTINES ---
****

```
STEP        TAU           TIME      OUTER RACE ROT  INNER RACE ROT
NO                        (S)          (DEG)           (DEG)
 0      0.000E+00      0.000E+00     0.000E+00       0.000E+00     Test tapered bearing
=====   ==========     ==========   ==========      ==========    ===================================
```

1. ROLLING ELEMENT PARAMETERS

RE NO	...ORBITAL POSITION (DEG)	....CONTACT ANGLE.... (DEG) OUTER RACE INNER RACE		....CONTACT LOAD..... (N) OUTER RACE INNER RACE		...CONTACT STRESS.... (PA) OUTER RACE INNER RACE		..MAJOR HALF WIDTH... (M) OUTER RACE INNER RACE		..MINOR HALF WIDTH... (M) OUTER RACE INNER RACE	
1	0.000E+00	1.300E+01	1.100E+01	1.057E+03	9.920E+02	6.115E+08	6.483E+08	5.598E-03	5.568E-03	9.824E-05	8.746E-05
2	1.636E+01	1.300E+01	1.100E+01	1.055E+03	9.901E+02	6.110E+08	6.478E+08	5.597E-03	5.567E-03	9.816E-05	8.739E-05
3	3.273E+01	1.300E+01	1.100E+01	1.049E+03	9.845E+02	6.095E+08	6.461E+08	5.594E-03	5.565E-03	9.793E-05	8.717E-05
4	4.909E+01	1.300E+01	1.100E+01	1.040E+03	9.757E+02	6.071E+08	6.434E+08	5.590E-03	5.561E-03	9.756E-05	8.681E-05
5	6.545E+01	1.300E+01	1.100E+01	1.029E+03	9.645E+02	6.041E+08	6.399E+08	5.585E-03	5.556E-03	9.709E-05	8.636E-05
6	8.182E+01	1.300E+01	1.100E+01	1.016E+03	9.517E+02	6.006E+08	6.359E+08	5.579E-03	5.550E-03	9.654E-05	8.584E-05
7	9.818E+01	1.300E+01	1.100E+01	1.003E+03	9.385E+02	5.969E+08	6.317E+08	5.573E-03	5.543E-03	9.597E-05	8.530E-05
8	1.145E+02	1.300E+01	1.100E+01	9.903E+02	9.258E+02	5.933E+08	6.277E+08	5.567E-03	5.538E-03	9.542E-05	8.478E-05
9	1.309E+02	1.300E+01	1.100E+01	9.792E+02	9.147E+02	5.902E+08	6.242E+08	5.562E-03	5.532E-03	9.494E-05	8.431E-05
10	1.473E+02	1.300E+01	1.100E+01	9.706E+02	9.060E+02	5.878E+08	6.214E+08	5.558E-03	5.528E-03	9.456E-05	8.395E-05
11	1.636E+02	1.300E+01	1.100E+01	9.651E+02	9.006E+02	5.862E+08	6.196E+08	5.556E-03	5.526E-03	9.432E-05	8.372E-05
12	1.800E+02	1.300E+01	1.100E+01	9.632E+02	8.987E+02	5.857E+08	6.190E+08	5.555E-03	5.525E-03	9.424E-05	8.364E-05
13	1.964E+02	1.300E+01	1.100E+01	9.651E+02	9.006E+02	5.862E+08	6.196E+08	5.556E-03	5.526E-03	9.432E-05	8.372E-05
14	2.127E+02	1.300E+01	1.100E+01	9.706E+02	9.060E+02	5.878E+08	6.214E+08	5.558E-03	5.528E-03	9.456E-05	8.395E-05
15	2.291E+02	1.300E+01	1.100E+01	9.792E+02	9.147E+02	5.902E+08	6.242E+08	5.562E-03	5.532E-03	9.494E-05	8.431E-05
16	2.455E+02	1.300E+01	1.100E+01	9.903E+02	9.258E+02	5.933E+08	6.277E+08	5.567E-03	5.538E-03	9.542E-05	8.478E-05
17	2.618E+02	1.300E+01	1.100E+01	1.003E+03	9.385E+02	5.969E+08	6.317E+08	5.573E-03	5.543E-03	9.597E-05	8.530E-05
18	2.782E+02	1.300E+01	1.100E+01	1.016E+03	9.517E+02	6.006E+08	6.359E+08	5.579E-03	5.550E-03	9.654E-05	8.584E-05
19	2.945E+02	1.300E+01	1.100E+01	1.029E+03	9.645E+02	6.041E+08	6.399E+08	5.585E-03	5.556E-03	9.709E-05	8.636E-05
20	3.109E+02	1.300E+01	1.100E+01	1.040E+03	9.757E+02	6.071E+08	6.434E+08	5.590E-03	5.561E-03	9.756E-05	8.681E-05
21	3.273E+02	1.300E+01	1.100E+01	1.049E+03	9.845E+02	6.095E+08	6.461E+08	5.594E-03	5.565E-03	9.793E-05	8.717E-05
22	3.436E+02	1.300E+01	1.100E+01	1.055E+03	9.901E+02	6.110E+08	6.478E+08	5.597E-03	5.567E-03	9.816E-05	8.739E-05

RE	...ORBITAL VELOCITY (RPM)	.......ANGULAR VELOCITY........ AMPLITUDE THETA PHI (RPM) (DEG) (DEG)			...RE ANG POSITION... THETA PHI (DEG) (DEG)		......SPIN/ROLL...... OUTER RACE INNER RACE		....CONTACT LOSS..... (N*M/S) OUTER RACE INNER RACE		..TIME AVE WEAR RATE (M**3/S)
1	1.147E+03	1.479E+04	-1.200E+01	0.000E+00	6.919E-16	0.000E+00	-2.175E-07	2.636E-07	3.211E-06	4.503E-06	1.536E-16
2	1.147E+03	1.479E+04	-1.200E+01	4.057E-16	2.251E-15	3.137E+00	-2.185E-07	2.627E-07	3.194E-06	4.479E-06	1.552E-16
3	1.147E+03	1.479E+04	-1.200E+01	2.888E-15	7.124E-16	3.462E+02	-2.214E-07	2.602E-07	3.147E-06	4.407E-06	1.565E-16
4	1.147E+03	1.479E+04	-1.200E+01	3.211E-15	7.074E-16	3.480E+02	-2.260E-07	2.562E-07	3.072E-06	4.295E-06	1.566E-16
5	1.147E+03	1.479E+04	-1.200E+01	3.600E+02	2.248E-15	3.588E+02	-2.319E-07	2.511E-07	2.978E-06	4.154E-06	1.555E-16
6	1.147E+03	1.479E+04	-1.200E+01	8.105E-16	2.253E-15	3.561E+02	-2.387E-07	2.452E-07	2.873E-06	3.995E-06	1.534E-16
7	1.147E+03	1.479E+04	-1.200E+01	3.600E+02	2.248E-15	3.592E+02	-2.457E-07	2.392E-07	2.767E-06	3.832E-06	1.504E-16
8	1.147E+03	1.479E+04	-1.200E+01	3.675E-15	7.181E-16	1.553E+01	-2.525E-07	2.333E-07	2.667E-06	3.679E-06	1.468E-16
9	1.147E+03	1.479E+04	-1.200E+01	3.600E+02	7.074E-16	1.201E+01	-2.584E-07	2.282E-07	2.581E-06	3.548E-06	1.429E-16
10	1.147E+03	1.479E+04	-1.200E+01	1.546E-15	9.809E-16	2.083E+02	-2.630E-07	2.242E-07	2.516E-06	3.447E-06	1.391E-16
11	1.147E+03	1.479E+04	-1.200E+01	5.095E-16	7.763E-16	3.330E+02	-2.659E-07	2.217E-07	2.475E-06	3.384E-06	1.356E-16
12	1.147E+03	1.479E+04	-1.200E+01	3.600E+02	6.919E-16	2.511E-14	-2.669E-07	2.208E-07	2.461E-06	3.362E-06	1.333E-16
13	1.147E+03	1.479E+04	-1.200E+01	3.600E+02	7.763E-16	3.330E+02	-2.659E-07	2.217E-07	2.475E-06	3.384E-06	1.356E-16
14	1.147E+03	1.479E+04	-1.200E+01	5.627E-16	9.809E-16	2.083E+02	-2.630E-07	2.242E-07	2.516E-06	3.447E-06	1.391E-16
15	1.147E+03	1.479E+04	-1.200E+01	1.832E-15	7.074E-16	1.201E+01	-2.584E-07	2.282E-07	2.581E-06	3.548E-06	1.429E-16
16	1.147E+03	1.479E+04	-1.200E+01	3.600E+02	7.181E-16	1.553E+01	-2.525E-07	2.333E-07	2.667E-06	3.679E-06	1.468E-16
17	1.147E+03	1.479E+04	-1.200E+01	1.158E-15	2.248E-15	3.592E+02	-2.457E-07	2.392E-07	2.767E-06	3.832E-06	1.504E-16
18	1.147E+03	1.479E+04	-1.200E+01	5.380E-16	2.253E-15	3.561E+02	-2.387E-07	2.452E-07	2.873E-06	3.995E-06	1.534E-16
19	1.147E+03	1.479E+04	-1.200E+01	3.600E+02	2.248E-15	3.588E+02	-2.319E-07	2.511E-07	2.978E-06	4.154E-06	1.555E-16
20	1.147E+03	1.479E+04	-1.200E+01	3.600E+02	7.074E-16	3.480E+02	-2.260E-07	2.562E-07	3.072E-06	4.295E-06	1.566E-16
21	1.147E+03	1.479E+04	-1.200E+01	3.245E-15	7.124E-16	3.462E+02	-2.214E-07	2.602E-07	3.147E-06	4.407E-06	1.565E-16
22	1.147E+03	1.479E+04	-1.200E+01	2.022E-15	2.251E-15	3.137E+00	-2.185E-07	2.627E-07	3.194E-06	4.479E-06	1.552E-16

RE	....SLIP VELOCITY....		.....TRAC COEFF......		....ISO LUB FILM.....		...THERMAL RED FAC...		......DRAG	..CHUR MOM	..NET LOSS
NO	(M/S)				(M)				(N)	(N*M)	(N*M/S)
	OUTER RACE	INNER RACE	OUTER RACE	INNER RACE	OUTER RACE	INNER RACE	OUTER RACE	INNER RACE			(DRAG+CHUR)
1	3.005E-03	3.286E-03	3.640E-05	4.745E-05	3.575E-06	3.343E-06	4.590E-01	4.561E-01			
2	2.999E-03	3.278E-03	3.631E-05	4.732E-05	3.576E-06	3.343E-06	4.590E-01	4.562E-01			
3	2.980E-03	3.255E-03	3.604E-05	4.694E-05	3.577E-06	3.344E-06	4.592E-01	4.563E-01			
4	2.951E-03	3.220E-03	3.563E-05	4.634E-05	3.578E-06	3.346E-06	4.593E-01	4.565E-01			
5	2.913E-03	3.175E-03	3.509E-05	4.557E-05	3.580E-06	3.347E-06	4.596E-01	4.568E-01			
6	2.869E-03	3.123E-03	3.449E-05	4.469E-05	3.582E-06	3.349E-06	4.599E-01	4.571E-01			
7	2.824E-03	3.069E-03	3.386E-05	4.379E-05	3.584E-06	3.352E-06	4.601E-01	4.574E-01			
8	2.781E-03	3.017E-03	3.326E-05	4.292E-05	3.586E-06	3.354E-06	4.604E-01	4.578E-01			
9	2.743E-03	2.971E-03	3.273E-05	4.217E-05	3.588E-06	3.355E-06	4.607E-01	4.580E-01			
10	2.714E-03	2.936E-03	3.233E-05	4.159E-05	3.589E-06	3.357E-06	4.609E-01	4.583E-01			
11	2.695E-03	2.913E-03	3.207E-05	4.122E-05	3.590E-06	3.357E-06	4.610E-01	4.584E-01			
12	2.689E-03	2.906E-03	3.198E-05	4.109E-05	3.590E-06	3.358E-06	4.610E-01	4.584E-01			
13	2.695E-03	2.913E-03	3.207E-05	4.122E-05	3.590E-06	3.357E-06	4.610E-01	4.584E-01			
14	2.714E-03	2.936E-03	3.233E-05	4.159E-05	3.589E-06	3.357E-06	4.609E-01	4.583E-01			
15	2.743E-03	2.971E-03	3.273E-05	4.217E-05	3.588E-06	3.355E-06	4.607E-01	4.580E-01			
16	2.781E-03	3.017E-03	3.326E-05	4.292E-05	3.586E-06	3.354E-06	4.604E-01	4.578E-01			
17	2.824E-03	3.069E-03	3.386E-05	4.379E-05	3.584E-06	3.352E-06	4.601E-01	4.574E-01			
18	2.869E-03	3.123E-03	3.449E-05	4.469E-05	3.582E-06	3.349E-06	4.599E-01	4.571E-01			
19	2.913E-03	3.175E-03	3.509E-05	4.557E-05	3.580E-06	3.347E-06	4.596E-01	4.568E-01			
20	2.951E-03	3.220E-03	3.563E-05	4.634E-05	3.578E-06	3.346E-06	4.593E-01	4.565E-01			
21	2.980E-03	3.255E-03	3.604E-05	4.694E-05	3.577E-06	3.344E-06	4.592E-01	4.563E-01			
22	2.999E-03	3.278E-03	3.631E-05	4.732E-05	3.576E-06	3.343E-06	4.590E-01	4.562E-01			

RE	.CONTACT DEFLECTION..		....RACE FLEXING.....		..CONTACT TEMP RISE..	
NO	(M)		(M)		(K)	
	OUTER RACE	INNER RACE	OUTER RACE	INNER RACE	OUTER RACE	INNER RACE
1	3.163E-06	2.999E-06	0.000E+00	0.000E+00	4.659E-05	6.770E-05
2	3.158E-06	2.994E-06	0.000E+00	0.000E+00	4.634E-05	6.731E-05
3	3.144E-06	2.980E-06	0.000E+00	0.000E+00	4.561E-05	6.617E-05
4	3.122E-06	2.957E-06	0.000E+00	0.000E+00	4.448E-05	6.440E-05
5	3.093E-06	2.928E-06	0.000E+00	0.000E+00	4.306E-05	6.217E-05
6	3.061E-06	2.896E-06	0.000E+00	0.000E+00	4.148E-05	5.967E-05
7	3.027E-06	2.861E-06	0.000E+00	0.000E+00	3.987E-05	5.714E-05
8	2.995E-06	2.828E-06	0.000E+00	0.000E+00	3.836E-05	5.476E-05
9	2.966E-06	2.799E-06	0.000E+00	0.000E+00	3.707E-05	5.272E-05
10	2.944E-06	2.777E-06	0.000E+00	0.000E+00	3.609E-05	5.117E-05
11	2.930E-06	2.763E-06	0.000E+00	0.000E+00	3.548E-05	5.019E-05
12	2.925E-06	2.758E-06	0.000E+00	0.000E+00	3.527E-05	4.986E-05
13	2.930E-06	2.763E-06	0.000E+00	0.000E+00	3.548E-05	5.019E-05
14	2.944E-06	2.777E-06	0.000E+00	0.000E+00	3.609E-05	5.117E-05
15	2.966E-06	2.799E-06	0.000E+00	0.000E+00	3.707E-05	5.272E-05
16	2.995E-06	2.828E-06	0.000E+00	0.000E+00	3.836E-05	5.476E-05
17	3.027E-06	2.861E-06	0.000E+00	0.000E+00	3.987E-05	5.714E-05
18	3.061E-06	2.896E-06	0.000E+00	0.000E+00	4.148E-05	5.967E-05
19	3.093E-06	2.928E-06	0.000E+00	0.000E+00	4.306E-05	6.217E-05
20	3.122E-06	2.957E-06	0.000E+00	0.000E+00	4.448E-05	6.440E-05
21	3.144E-06	2.980E-06	0.000E+00	0.000E+00	4.561E-05	6.617E-05
22	3.158E-06	2.994E-06	0.000E+00	0.000E+00	4.634E-05	6.731E-05

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STEP        TAU           TIME      OUTER RACE ROT  INNER RACE ROT
NO                        (S)          (DEG)           (DEG)
  0       0.000E+00     0.000E+00    0.000E+00       0.000E+00      Test tapered bearing
=====   ==========    ==========   ==========      ==========      ====================================
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1A. LOAD DISTRIBUTION ALONG ROLLER NO. 1

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..................OUTER RACE CONTACT..................  ..................INNER RACE CONTACT..................
   AXIAL POS  GEO INT HALF WIDTH  NOR LOAD  TRAC LOAD  AXIAL POS  GEO INT HALF WIDTH  NOR LOAD  TRAC LOAD
     (M)        (M)      (M)        (N/M)     (N/M)      (M)        (M)      (M)        (N/M)     (N/M)

 1 -5.267E-03 1.064E-06 5.618E-05 2.997E+04 1.091E+00 -5.238E-03 1.053E-06 5.116E-05 2.962E+04 -1.406E+00
 2 -4.537E-03 3.163E-06 1.028E-04 1.005E+05 6.055E-03 -4.513E-03 2.999E-06 9.142E-05 9.474E+04 -1.055E-02
 3 -3.586E-03 3.163E-06 1.027E-04 1.005E+05 4.838E-03 -3.566E-03 2.999E-06 9.133E-05 9.474E+04 -8.433E-03
 4 -2.856E-03 3.163E-06 1.026E-04 1.005E+05 3.900E-03 -2.841E-03 2.999E-06 9.125E-05 9.474E+04 -6.799E-03
 5 -2.273E-03 3.163E-06 1.026E-04 1.005E+05 3.147E-03 -2.261E-03 2.999E-06 9.119E-05 9.474E+04 -5.487E-03
 6 -8.148E-04 3.163E-06 1.024E-04 1.005E+05 1.249E-03 -8.098E-04 2.999E-06 9.105E-05 9.474E+04 -2.178E-03
 7  1.088E-03 3.163E-06 1.022E-04 1.005E+05 -1.257E-03  1.083E-03 2.999E-06 9.086E-05 9.474E+04  2.194E-03
 8  2.547E-03 3.163E-06 1.020E-04 1.005E+05 -3.200E-03  2.534E-03 2.999E-06 9.071E-05 9.474E+04  5.587E-03
 9  3.130E-03 3.163E-06 1.019E-04 1.005E+05 -3.983E-03  3.114E-03 2.999E-06 9.065E-05 9.474E+04  6.954E-03
10  3.859E-03 3.163E-06 1.019E-04 1.005E+05 -4.966E-03  3.840E-03 2.999E-06 9.058E-05 9.474E+04  8.673E-03
11  4.811E-03 3.163E-06 1.017E-04 1.005E+05 -6.257E-03  4.786E-03 2.999E-06 9.048E-05 9.474E+04  1.093E-02
12  5.540E-03 1.064E-06 5.551E-05 2.997E+04 1.105E+00  5.512E-03 1.053E-06 5.055E-05 2.962E+04 -1.427E+00
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1B. RACE FLANGE INTERACTION

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RE ...................................ROLLER/INNER RACE FLANGE INTERACTION.......................................
NO   GEOM INTERACTION      CONTACT LOAD     MAJOR HALF WIDTH    MINOR HALF WIDTH      CONTACT LOSS     CONTACT
        (M)                    (N)               (M)                 (M)               (N*M/S)          CODE
    FLANGE I  FLANGE II   FLANGE I  FLANGE II  FLANGE I  FLANGE II  FLANGE I  FLANGE II  FLANGE I  FLANGE II  I II

 1 -9.089E-07 0.000E+00 4.957E+01 0.000E+00 3.866E-04 0.000E+00 3.807E-04 0.000E+00 1.176E+01 0.000E+00  0 0
 2 -9.081E-07 0.000E+00 4.951E+01 0.000E+00 3.864E-04 0.000E+00 3.805E-04 0.000E+00 1.165E+01 0.000E+00  0 0
 3 -9.057E-07 0.000E+00 4.931E+01 0.000E+00 3.859E-04 0.000E+00 3.800E-04 0.000E+00 1.135E+01 0.000E+00  0 0
 4 -9.019E-07 0.000E+00 4.900E+01 0.000E+00 3.851E-04 0.000E+00 3.792E-04 0.000E+00 1.086E+01 0.000E+00  0 0
 5 -8.971E-07 0.000E+00 4.861E+01 0.000E+00 3.841E-04 0.000E+00 3.782E-04 0.000E+00 1.019E+01 0.000E+00  0 0
 6 -8.916E-07 0.000E+00 4.817E+01 0.000E+00 3.829E-04 0.000E+00 3.770E-04 0.000E+00 9.387E+00 0.000E+00  0 0
 7 -8.859E-07 0.000E+00 4.770E+01 0.000E+00 3.817E-04 0.000E+00 3.758E-04 0.000E+00 8.483E+00 0.000E+00  0 0
 8 -8.804E-07 0.000E+00 4.726E+01 0.000E+00 3.805E-04 0.000E+00 3.746E-04 0.000E+00 7.541E+00 0.000E+00  0 0
 9 -8.755E-07 0.000E+00 4.687E+01 0.000E+00 3.794E-04 0.000E+00 3.736E-04 0.000E+00 6.639E+00 0.000E+00  0 0
10 -8.718E-07 0.000E+00 4.657E+01 0.000E+00 3.786E-04 0.000E+00 3.728E-04 0.000E+00 5.876E+00 0.000E+00  0 0
11 -8.694E-07 0.000E+00 4.638E+01 0.000E+00 3.781E-04 0.000E+00 3.723E-04 0.000E+00 5.359E+00 0.000E+00  0 0
12 -8.686E-07 0.000E+00 4.631E+01 0.000E+00 3.779E-04 0.000E+00 3.721E-04 0.000E+00 5.175E+00 0.000E+00  0 0
13 -8.694E-07 0.000E+00 4.638E+01 0.000E+00 3.781E-04 0.000E+00 3.723E-04 0.000E+00 5.359E+00 0.000E+00  0 0
14 -8.718E-07 0.000E+00 4.657E+01 0.000E+00 3.786E-04 0.000E+00 3.728E-04 0.000E+00 5.876E+00 0.000E+00  0 0
15 -8.755E-07 0.000E+00 4.687E+01 0.000E+00 3.794E-04 0.000E+00 3.736E-04 0.000E+00 6.639E+00 0.000E+00  0 0
16 -8.804E-07 0.000E+00 4.726E+01 0.000E+00 3.805E-04 0.000E+00 3.746E-04 0.000E+00 7.541E+00 0.000E+00  0 0
17 -8.859E-07 0.000E+00 4.770E+01 0.000E+00 3.817E-04 0.000E+00 3.758E-04 0.000E+00 8.483E+00 0.000E+00  0 0
18 -8.916E-07 0.000E+00 4.817E+01 0.000E+00 3.829E-04 0.000E+00 3.770E-04 0.000E+00 9.387E+00 0.000E+00  0 0
19 -8.971E-07 0.000E+00 4.861E+01 0.000E+00 3.841E-04 0.000E+00 3.782E-04 0.000E+00 1.019E+01 0.000E+00  0 0
20 -9.019E-07 0.000E+00 4.900E+01 0.000E+00 3.851E-04 0.000E+00 3.792E-04 0.000E+00 1.086E+01 0.000E+00  0 0
21 -9.057E-07 0.000E+00 4.931E+01 0.000E+00 3.859E-04 0.000E+00 3.800E-04 0.000E+00 1.135E+01 0.000E+00  0 0
22 -9.081E-07 0.000E+00 4.951E+01 0.000E+00 3.864E-04 0.000E+00 3.805E-04 0.000E+00 1.165E+01 0.000E+00  0 0
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1C. ROLLER END AND RACE FLANGE WEAR DISTRIBUTION

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RE  TIME AVE WEAR RATE..    RE  TIME AVE WEAR RATE..    RE  TIME AVE WEAR RATE..    RE  TIME AVE WEAR RATE..
NO       (M**3/S)           NO       (M**3/S)           NO       (M**3/S)           NO       (M**3/S)
    END I     END II            END I     END II            END I     END II            END I     END II

 1 9.835E-13 0.000E+00      2  9.752E-13 0.000E+00      3  9.508E-13 0.000E+00      4  9.116E-13 0.000E+00
 5 8.600E-13 0.000E+00      6  7.990E-13 0.000E+00      7  7.323E-13 0.000E+00      8  6.645E-13 0.000E+00
 9 6.009E-13 0.000E+00     10  5.477E-13 0.000E+00     11  5.118E-13 0.000E+00     12  4.991E-13 0.000E+00
13 5.118E-13 0.000E+00     14  5.477E-13 0.000E+00     15  6.009E-13 0.000E+00     16  6.645E-13 0.000E+00
17 7.323E-13 0.000E+00     18  7.990E-13 0.000E+00     19  8.600E-13 0.000E+00     20  9.116E-13 0.000E+00
21 9.508E-13 0.000E+00     22  9.752E-13 0.000E+00

      ......TIME AVE RACE FLANGE WEAR RATES......
                     (M**3/S)
        OUTER I    OUTER II    INNER I    INNER II
       0.000E+00  0.000E+00  1.659E-11  0.000E+00
```

STEP	TAU	TIME	OUTER RACE ROT	INNER RACE ROT	
NO		(S)	(DEG)	(DEG)	
0	0.000E+00	0.000E+00	0.000E+00	0.000E+00	Test tapered bearing
=====	==========	==========	==========	==========	====================================

2. RACE AND CAGE PARAMETERS

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        RE ................RE/CAGE INTERACTION..................
        NO C   GEO INT   CONTACT   CONTACT   CONTACT   CONTACT   TIME AVE
           C             FORCE     POS 1     POS 2     LOSS      WEAR RATE
                  (M)     (N)       (M)       (M)      (N*M/S)   (M**3/S)
```

RE NO	C C	GEO INT (M)	CONTACT FORCE (N)	CONTACT POS 1 (M)	CONTACT POS 2 (M)	CONTACT LOSS (N*M/S)	TIME AVE WEAR RATE (M**3/S)
1	0	4.336E-04	0.000E+00	-1.709E-02	9.070E-04	0.000E+00	0.000E+00
	0	4.336E-04	0.000E+00	-1.709E-02	-9.070E-04	0.000E+00	0.000E+00
2	0	4.055E-04	0.000E+00	-1.709E-02	9.030E-04	0.000E+00	0.000E+00
	0	4.617E-04	0.000E+00	-1.709E-02	-9.030E-04	0.000E+00	0.000E+00
3	0	3.797E-04	0.000E+00	-1.709E-02	8.915E-04	0.000E+00	0.000E+00
	0	4.875E-04	0.000E+00	-1.709E-02	-8.915E-04	0.000E+00	0.000E+00
4	0	3.582E-04	0.000E+00	-1.709E-02	8.733E-04	0.000E+00	0.000E+00
	0	5.089E-04	0.000E+00	-1.708E-02	-8.733E-04	0.000E+00	0.000E+00
5	0	3.428E-04	0.000E+00	-1.709E-02	8.499E-04	0.000E+00	0.000E+00
	0	5.242E-04	0.000E+00	-1.708E-02	-8.499E-04	0.000E+00	0.000E+00
6	0	3.348E-04	0.000E+00	-1.709E-02	8.232E-04	0.000E+00	0.000E+00
	0	5.322E-04	0.000E+00	-1.708E-02	-8.232E-04	0.000E+00	0.000E+00
7	0	3.347E-04	0.000E+00	-1.708E-02	7.954E-04	0.000E+00	0.000E+00
	0	5.321E-04	0.000E+00	-1.707E-02	-7.954E-04	0.000E+00	0.000E+00
8	0	3.427E-04	0.000E+00	-1.708E-02	7.687E-04	0.000E+00	0.000E+00
	0	5.241E-04	0.000E+00	-1.707E-02	-7.687E-04	0.000E+00	0.000E+00
9	0	3.580E-04	0.000E+00	-1.708E-02	7.453E-04	0.000E+00	0.000E+00
	0	5.087E-04	0.000E+00	-1.707E-02	-7.453E-04	0.000E+00	0.000E+00
10	0	3.794E-04	0.000E+00	-1.707E-02	7.271E-04	0.000E+00	0.000E+00
	0	4.872E-04	0.000E+00	-1.707E-02	-7.271E-04	0.000E+00	0.000E+00
11	0	4.052E-04	0.000E+00	-1.707E-02	7.155E-04	0.000E+00	0.000E+00
	0	4.614E-04	0.000E+00	-1.707E-02	-7.155E-04	0.000E+00	0.000E+00
12	0	4.333E-04	0.000E+00	-1.707E-02	7.116E-04	0.000E+00	0.000E+00
	0	4.333E-04	0.000E+00	-1.707E-02	-7.116E-04	0.000E+00	0.000E+00
13	0	4.614E-04	0.000E+00	-1.707E-02	7.155E-04	0.000E+00	0.000E+00
	0	4.052E-04	0.000E+00	-1.707E-02	-7.155E-04	0.000E+00	0.000E+00
14	0	4.872E-04	0.000E+00	-1.707E-02	7.271E-04	0.000E+00	0.000E+00
	0	3.794E-04	0.000E+00	-1.707E-02	-7.271E-04	0.000E+00	0.000E+00
15	0	5.087E-04	0.000E+00	-1.707E-02	7.453E-04	0.000E+00	0.000E+00
	0	3.580E-04	0.000E+00	-1.708E-02	-7.453E-04	0.000E+00	0.000E+00
16	0	5.241E-04	0.000E+00	-1.707E-02	7.687E-04	0.000E+00	0.000E+00
	0	3.427E-04	0.000E+00	-1.708E-02	-7.687E-04	0.000E+00	0.000E+00
17	0	5.321E-04	0.000E+00	-1.707E-02	7.954E-04	0.000E+00	0.000E+00
	0	3.347E-04	0.000E+00	-1.708E-02	-7.954E-04	0.000E+00	0.000E+00
18	0	5.322E-04	0.000E+00	-1.708E-02	8.232E-04	0.000E+00	0.000E+00
	0	3.348E-04	0.000E+00	-1.709E-02	-8.232E-04	0.000E+00	0.000E+00
19	0	5.242E-04	0.000E+00	-1.708E-02	8.499E-04	0.000E+00	0.000E+00
	0	3.428E-04	0.000E+00	-1.709E-02	-8.499E-04	0.000E+00	0.000E+00
20	0	5.089E-04	0.000E+00	-1.708E-02	8.733E-04	0.000E+00	0.000E+00
	0	3.582E-04	0.000E+00	-1.709E-02	-8.733E-04	0.000E+00	0.000E+00
21	0	4.875E-04	0.000E+00	-1.709E-02	8.915E-04	0.000E+00	0.000E+00
	0	3.797E-04	0.000E+00	-1.709E-02	-8.915E-04	0.000E+00	0.000E+00
22	0	4.617E-04	0.000E+00	-1.709E-02	9.030E-04	0.000E+00	0.000E+00
	0	4.055E-04	0.000E+00	-1.709E-02	-9.030E-04	0.000E+00	0.000E+00

LAND NO	C C	NORMAL (N)	TRACTION (N)	CON ANGLE (DEG)	ATT ANGLE (DEG)	RACE/CAGE GEO INT (M)	RACE/CAGE SLIP VEL (M/S)	EFFECTIVE DIA PLAY (M)	CONTACT LOSS (N*M/S)	TIME AVE WEAR RATE (M**3/S)
2	0	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.986E-04	0.000E+00	5.973E-04	0.000E+00	0.000E+00

	AXIAL (M)	RADIAL (M)	ORBITAL (DEG)	VELOCITY (RPM)	AMPLITUDE (RPM)	THETA (DEG)	PHI (DEG)	THETA (DEG)	PHI (DEG)	HOOP STRESS (PA)	TIME AVE WEAR RATE (M**3/S)
CAGE	1.402E-05	9.975E-05	1.800E+02	1.147E+03	1.147E+03	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
ORACE	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.524E-15
IRACE	2.060E-05	2.465E-07	0.000E+00	0.000E+00	2.500E+03	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3.728E+06	1.747E-15

STEP	TAU	TIME	OUTER RACE ROT	INNER RACE ROT	
NO		(S)	(DEG)	(DEG)	
0	0.000E+00	0.000E+00	0.000E+00	0.000E+00	Test tapered bearing
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3. APPLIED PARAMETERS

	.........APPLIED FORCES.........			.......APPLIED MOMENTS........						
	(N)	(N)	(N)	(N*M)	(N*M)	(N*M)	BASIC FATIGUE LIFE	(HOURS)	5.771E+04
	COMP-X	COMP-Y	COMP-Z	COMP-X	COMP-Y	COMP-Z	MODIFIED FATIGUE LIFE	(HOURS)	1.731E+05
							INTERNAL CLEARANCE	(M)	0.000E+00
							OUTER RACE FIT	(M)	0.000E+00
							INNER RACE FIT	(M)	-1.550E-06
CAGE	0.000E+00	0.000E+00	-2.956E+00	0.000E+00	0.000E+00	0.000E+00			
ORACE	4.997E+03	-8.415E-04	4.999E+02	2.203E-03	1.165E+01	-2.683E-08	TOTAL POWER LOSS	(N*M/S)	1.916E+02
IRACE	-5.001E+03	5.221E-01	-4.999E+02	-9.509E-01	-1.002E+01	-7.998E-03	CHURNING LOSS FRACTION		0.000E+00

4. TIME STEP SUMMARY

					....................TIME AVERAGE PARAMETERS....................				
STEP	TIME	OUTER RACE	INNER RACE	FATIGUE	POWER	RE ORBITAL	CAGE OMEGA	CAGE WHIRL	CAGE
NO		ROTATION	ROTATION	LIFE	LOSS	VEL RATIO	RATIO	RATIO	WEAR RATE
	(S)	(DEG)	(DEG)	(HOURS)	(N*M/S)				(M**3/S)
0	0.000E+00	0.000E+00	0.000E+00	1.731E+05	1.916E+02	4.589E-01	4.589E-01	4.589E-01	0.000E+00